Semi- and Super-Cathode-Driven Amplifiers

BY WILLIAM I. ORR,* W6SAI AND WILLIAM H. SAYER, WA6BAN**

In a previous article covering problems peculiar to cathode-driven ("grounded-grid") amplifiers[1] it was pointed out that when well-shielded tubes are operated in cathode-driven circuits in the h.f. region, neutralization is not always necessary for achieving circuit stability in properly designed equipment. If required, neutralization could be easily applied in one or more forms. The cathode-driven amplifier, moreover, permits the designer to include a degree of additional negative or positive feedback, in the form of grid driving voltage, to establish desired operating conditions. Specifically, the applied grid voltage may be used to vary the power gain and so-called "feed-through" power of the amplifier and, in a special case for tetrode and pentode tubes, this permits the elimination of the screen supply, screen power being taken from the r.f. drive. Circuits that make use of auxiliary grid-drive voltage are termed *semi-* and *super-cathode* driven. This article discusses the application of these circuits to amateur practice.

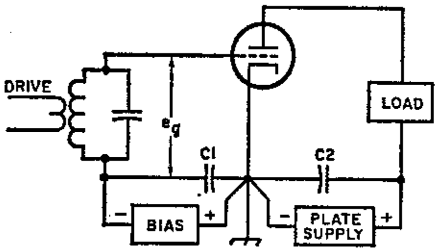


Fig. 1—The grid-driven amplifier. Drive signal (e_g) is applied between grid and cathode. When the grid is positive with respect to ground, plate potential becomes more negative with respect to the cathode (ground). Instantaneous plate voltage is out of phase with grid drive voltage, and the two circuits are common only at the cathode (ground) point. Bias and plate power supplies are considered in the circuit for d.c. and out of the circuit from an r.f. point of view, by virtue of bypass capacitors C_1 and C_2. Class of operation is determined by bias and drive signal voltage levels.

The Grid-Driven Circuit

The grid-driven circuit is a good place to start investigation.

Fig. 1 is a block diagram of a conventional grid-driven triode amplifier. For simplification, neutralization is not shown, and power and r.f. circuits are greatly simplified. The driving signal, e_g, is applied between grid and cathode (ground).

Operating conditions for linear amplifiers exist which offer advantages to the circuit designer and equipment user. Power gain and "feed-through" power of the stage may be varied, and reduced intermodulation distortion is achieved by manipulation of the ratio of cathode to grid drive, as discussed in this article.

In a perfect amplifier, input and output tuning adjustments are independent of each other and the grid and plate voltages are 180 degrees out of phase.

Driving power is the amount of signal power dissipated by the grid, if the grid is driven sufficiently positive to attract electrons from the cathode, plus any power demanded by various circuit losses. The class of operation is defined by bias voltage and driving-signal level. In the case of Class AB_1 operation, grid-drive requirements are very low because the grid is never driven positive and therefore no grid current is drawn. Class AB_2 or class B operation may call for a moderate amount of driving power on positive signal peaks when grid current is drawn. For Class A and B modes of operation, the output waveform is a replica of the input waveform, and the circuit may be used for linear amplification. When the circuit is adjusted for Class C operation (with bias greater than the cutoff value and plate current flowing in pulses less than one-half an operating cycle) the linear relationship between input and output signal no longer exists and the operating parameters are unsuited for linear amplification.

The Cathode-Driven Circuit

Fig. 2A illustrates a triode amplifier, simplified as previously explained, in which the drive signal e_c is applied between grid and cathode, with the grid grounded with respect to the r.f. signal. Operation of this *circuit* is strikingly different than that of the grid-driven configuration of Fig. 1, but *tube* operation is the same. That is to say, when the grid is driven positive in either case, the cathode is driven negative and plate current flows. The mode of operation is, of course, determined as before by choice of bias and drive signal levels.

In the linear mode, if it is assumed that the cathode is driven negative with respect to the grid (r.f. ground), the grid is then positive in relation to the cathode. With a positive grid signal, the plate becomes more negative with

---

*Manager, Amateur Service Dept. Eimac, Division of Varian, San Carlos, Calif.

**Project Engineer, Industrial Application Div., Eimac, Division of Varian, San Carlos, Calif.

[1] Orr and Sayer, "The Cathode-Driven Amplifier", *QST*, June, 1967.

respect to both cathode and ground. On the other half of the operating cycle, when the cathode is positive with respect to the grid, the plate becomes more positive in relation to ground. Thus the plate potential responds in like polarity to the cathode-drive signal. During the time that the cathode is driven negative, converted drive voltage is added to the d.c. plate potential, as shown in Fig. 2B. An extra amount of instantaneous plate voltage is developed in series and in phase with the cathode signal. The driver, then, may be pictured as a second plate supply effectively in series with the main plate supply of the amplifier. The portion of *converted drive power* which appears in the plate circuit as additional r.f. output is commonly called "feed-through" power, even though it does not "feed through" anything. The effective d.c. plate-to-cathode voltage on the cathode-driven tube during negative signal excursions of the cathode voltage is the sum of the d.c. plate voltage and the r.m.s. value of the cathode voltage, e_c. During positive signal excursions (when the grid is negative with respect to the cathode) the tube is cut off, so the subtractive portion of the drive voltage during this part of the operating cycle is ineffective.

The plate voltage of the cathode-driven amplifier thus varies over the operating cycle, deviating from the nominal power supply value to a somewhat higher value in accord with the modulation envelope of the drive signal. The value of converted drive power in the plate circuit is approximately the product of the r.m.s. cathode voltage and the d.c. plate current ($e_c \times I_p$). The total drive requirement is the sum of grid-drive power, converted drive-signal power, and grid-circuit losses. Grid-drive power and grid-circuit losses remain relatively constant in either mode of operation, the extra converted grid-drive power appearing only in the cathode-driven mode.

As in the grid-driven case, the cathode-driven amplifier may be operated Class A, B or C by proper choice of bias and drive-signal level. High-μ triodes and *some* tetrodes may be operated in near Class B condition, with zero grid bias and screen grounded. This subtle distinction should again be emphasized: Circuit configuration and operating mode are two separate and distinct things, and the use of the loose, inclusive term "grounded-grid" tends to blur and confuse the distinction. A circuit may be cathode driven, but is not necessarily "grounded-grid" from either an r.f. or d.c. point of view.

Envelope Modulation

Comparison of the operating parameters of grid-driven and cathode-driven circuits utilizing the same tube type in the same class of operation reveals that drive requirements of the tube are identical, with the obvious exception of the converted drive power which is a characteristic of the cathode-driven circuit. When comparing stage gains between the two modes of operation, the additional converted-drive-power requirement of the cathode-driven stage effectively reduces the overall power gain of the circuit and provides a degree of inverse r.f. feedback roughly equal to the reduction of stage gain.

In the case of tetrode and pentode tubes, a portion of the converted drive power is used to supply screen power as well as plate power during negative drive-signal excursions. This is why such tubes operating in cathode-driven service usually have reduced d.c. screen voltage: the remainder of the required screen voltage is supplied by the driving source, reaching the desired maximum value at the peak of the driving signal (an example is the Collins 30S-1 amplifier, which utilizes a Class AB$_1$ 4CX1000A tetrode in this circuit).

R.f. envelope modulation resulting from envelope variations of plate and screen voltage affords a degree of inverse feedback not easily obtainable in a grid-driven stage. A reduction of intermodulation distortion has been observed for various tetrode tubes operated in this fashion, amounting to 3 to 10 decibels improvement in unwanted third-order products.

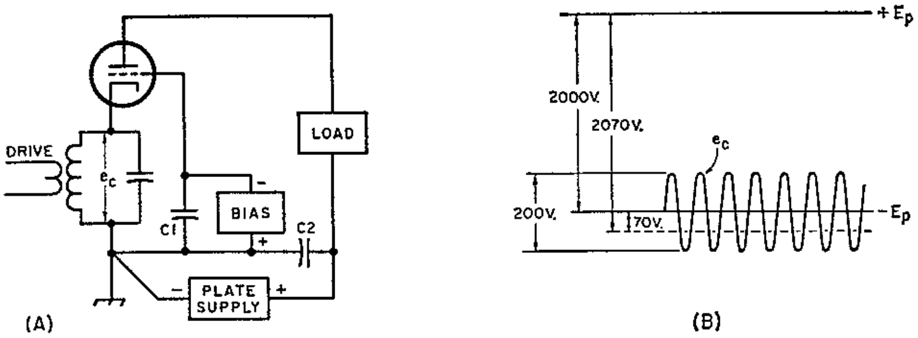


Fig. 2—The cathode-driven amplifier. (A) Drive signal (e_c) is applied between cathode and grid (r.f. ground). When the cathode is driven positive with respect to the grid, the plate potential becomes more positive in relation to ground. Instantaneous plate voltage is in phrase with cathode drive and in series with it, from a d.c. point of view. (B) Effective plate voltage during the negative portion of the cathode drive signal is the sum of the d.c. potential plus the r.m.s. value of the converted drive voltage. In this case, d.c. plate voltage is 2000, peak-to-peak r.f. drive voltage is 200, and r.m.s. drive voltage is 70. The effective plate voltage is 2070.

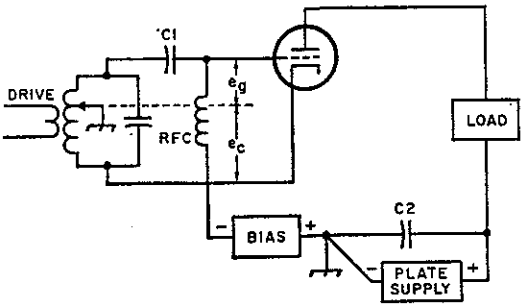


Fig. 3—The semi-cathode-driven amplifier. Auxiliary drive voltage (e_g) is applied to the grid out of phase with the cathode signal (e_c), raising the stage gain and lowering the converted drive power. Total drive requirement is reduced as the proportion of grid to cathode excitation is raised. When e_g is large compared to e_c, the circuit resembles a grid-driven stage, with e_c serving to boost drive level and reduce stage gain over simple grid-driven requirements.

Semi-Cathode-Driven Operation

Operating modes between grid-driven and cathode-driven states are possible by movement of the ground point to positions between the configurations of Figs. 1 and 2. The r.f. ground return is thus electrically placed between the grid and cathode of the tube (Fig. 3). This configuration is termed semi-cathode-driven service. In this mode of operation, a portion e_g of the drive signal is applied to the control grid out of phase with the cathode signal, e_c. While the total grid-to-cathode driving voltage remains the same no matter where the ground point is placed, the ratio of cathode volts to grid volts varies with the position of the ground return. The limiting condition is reached, of course, when the cathode is at r.f. ground and full drive is applied to the grid of the tube. At intermediate points the degree of converted drive power varies directly with respect to the cathode drive voltage. Stage gain is inversely related to cathode drive voltage, and the total drive power is closely related to cathode drive voltage. Thus, stage gain is enhanced and total drive power is reduced as the circuit departs from the cathode-driven mode and approaches the grid-driven mode.

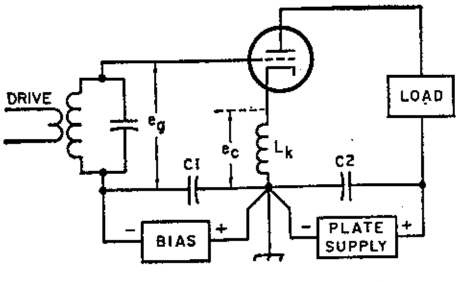


Fig. 4—Grid-driven amplifier having cathode lead inductance. Drive voltage, e_g, flowing through input circuit creates voltage drop (e_c) across cathode lead inductance, L_k, by virtue of cathode r.f. current. Cathode voltage tends to oppose grid drive, lowering power gain of stage and making it more difficult to drive.

In other words, if an auxiliary voltage, out of phase with the cathode signal, is applied to the control grid of a cathode-driven stage it will boost stage gain and reduce converted drive power. This is a very convenient scheme to match the drive level of a linear amplifier stage to the power output of a given exciter, if the output of the latter tends to be marginal.

Looking at the other side of the coin, it can be realized that introduction of out-of-phase cathode-drive voltage into a grid-driven stage will tend to lower the power gain of the stage, making it more difficult to excite, as excitation power must be translated into converted drive power. This is exactly the case in v.h.f. amplifiers having excessive cathode lead inductance across which a portion of the drive signal is developed (Fig. 4). Cathode lead inductance, in other words, robs the v.h.f. amplifier of grid drive because it converts needed excitation into converted drive power appearing in the plate circuit, thus effectively lowering the power gain of the stage and boosting the excitation level required for a given value of power output.

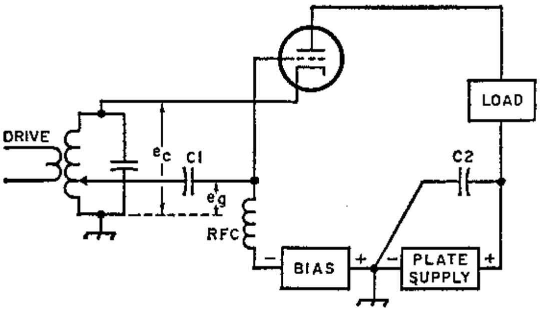


Fig. 5—Super-cathode-driven amplifier. Drive voltage, e_c, is applied to cathode, and a portion, e_g, is applied to the grid in phase with cathode signal. Stage gain is lowered and converted drive power is raised. This circuit may be used to absorb extra driving power of exciter and convert it to plate-circuit power.

By judicious division of the drive signal between grid and cathode of an amplifier stage it is possible to balance the drive requirement with the available power from the exciter. Many modern s.s.b. linear amplifiers make use of cathode-driven circuitry, but the drive requirement is something of a hit-or-miss situation. If the s.s.b. exciter is modest in power output, it is possible to raise the power gain (reduce the converted drive requirement) of a particular "grounded-grid" amplifier by introducing out-of-phase drive voltage into the grid circuit, effectively "matching" the drive requirement of the amplifier to the power capability of the exciter.

Super-Cathode-Driven Operation

Shown in Fig. 5 is a circuit in which a portion, e_g, of the total drive signal is applied in phase to the grid of a cathode-driven amplifier to effectively oppose the cathode voltage. This is

TABLE I

4CX300A, Class B, Typical Super-Cathode-Driven Service

Plate Voltage	2000
Grid Voltage	0
Screen Voltage	330 (peak)
D.C. Plate Current	
no signal	15 ma.
max. signal	250 ma.
Drive Power	75 watts
Measured Power Output	375 watts
Intermodulation Distortion Products:	
3rd order =	−46 db.
5th order =	−49 db.

4CX300A, Class AB_1, Typical Grid-Driven Service

Plate Voltage	2000
Screen Voltage	350
Grid Voltage	−55
D.C. Plate Current	
no signal	100 ma.
max. signal	250 ma.
Drive Power	0 watts
Measured Power Output	300 watts
Intermodulation Distortion Products:	
3rd order =	−27 db.
5th order =	−36 db.

termed super-cathode-driven operation. Drive power is increased and stage gain is decreased, as compared to a conventional cathode-driven circuit. It may appear fatuous to design an amplifier which demands more than the minimum driving power; however, this circuit may be used to advantage when it is necessary to absorb excess drive power from the exciter, over and above that value required by normal drive and "feed-through." The circuit, moreover, has other advantages that make it appealing to the circuit designer. An early s.s.b. transmitter design, for example, had series-connected super-cathode-driven low-μ tubes adjusted so that the drive power contributed by the first stage and amplified by the second stage equalled the power supplied by the second stage. Each stage thus contributed 50 per cent of the total output power, permitting the transmitter to make use of four tubes in a two-stage amplifier, neither stage being individually capable of producing the desired power level.

The Super-Cathode-Driven Tetrode

When used with a tetrode or pentode tube, super-cathode service permits the cathode driving signal to serve as a screen power source. Screen-to-cathode voltage (e_{sg}) is supplied on alternate half-cycles of the drive signal as shown in Fig. 6. The control grid may be driven (tied to the cathode) or tapped to a point on the cathode circuit. In the former case, the tube resembles a low-μ triode having an abnormally high converted-drive-power characteristic combined with an unusually low value of static plate current. (Static plate current, of course, is low because static screen voltage is zero.) Operating data for a 4CX300A in this mode are given in Table I. Note the great degree of improvement in intermodulation distortion as compared to grid-driven service. Super-cathode drive requirement is high, but a large proportion of this is converted to output power as indicated.

The super-cathode-driven tetrode circuit of Fig. 6 may be modified by the inclusion of screen and bias voltages to shift the operation to near Class AB_1. Power gain rises and rectified drive power drops as this shift is made. Screen and grid potentials, in fact, may be varied to match the power gain of the stage to a predetermined

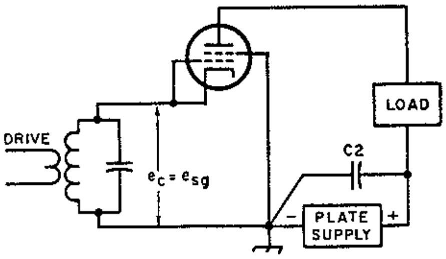
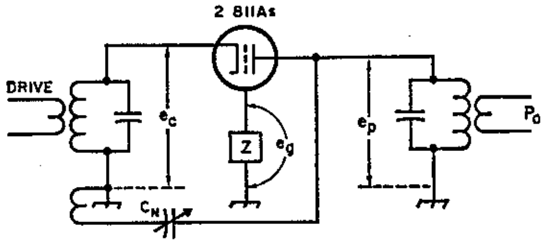


Fig. 6—Super-cathode-driven tetrode amplifier. Tetrode tube may be strapped as a triode with control grid tied to the cathode. Drive voltage, e_c, serves as screen voltage, e_{sg}, since screen is at ground potential. Resting plate current is low as screen voltage is zero with no drive signal. Converted drive power is large, as is total grid drive requirement. Screen and control-grid bias voltages may be added to this circuit to raise power gain of tube and decrease total drive requirement.

TABLE II

Two 811A, Class B, Cathode-Driven, Neutralized (values for two tubes given)	$Z = 0$, $e_g = 0$	$Z = 75\ \mu\mu$f./tube $e_g = 70$ volts, r.m.s.
Plate Voltage	1500	1500
D.C. Plate Current	335 ma.	335 ma.
Power Input	500 watts	500 watts
Grid Current	50 ma.	50 ma.
Plate Load	3000 ohms	3000 ohms
Drive Power (total)	25 watts	50 watts
e_c (r.m.s.)	61	130
e_g (r.m.s.)	0	70
e_p (r.m.s.)	980	1080
Converted Driver Power	20 watts	46.5 watts
Power Output	322 watts	386 watts



drive level, falling between the very low requirement of Class AB$_1$ service and the rather large Class B requirement specified in Table I. Power gain is set by screen-voltage adjustment, and the static plate current is determined by the bias level.

Plate-Circuit Feedback

The circuits discussed so far are special instances of the general circuit of Fig. 3 where the control grid of a cathode-driven amplifier is lifted above r.f. ground to permit the injection of an auxiliary drive signal. The previously-mentioned circuits are ones in which the feedback voltage is derived from the driving signal. It is also possible to derive the feedback voltage from the output signal of the stage, with the tube included in the feedback loop.

In the circuit of Fig. 7A, the feedback signal is applied to the grid of a cathode-driven stage. Generally speaking, external feedback is not applied to the tube element receiving the drive signal: applying it to separate element minimizes the reaction of the feedback signal upon the driving source. If the feedback is in, or out of, phase with plate and cathode signals, amplifier operation is comparable with that of the super- and semi-cathode-driven circuits discussed earlier.

The degree of feedback is determined by the capacitance ratio C_1/C_2. In normal practice, C_1 is of the order of 1 to 5 pf. and C_2 may fall in the range of 100 to 500 pf. The greater the capacitance of C_2 as compared with C_1 the less will be the feedback signal at the grid of the tube.

This feedback technique is used in the Collins 30L-1 amplifier to match the drive requirement of four cathode-driven 811A tubes to the nominal power output of the S-line exciter (about 100

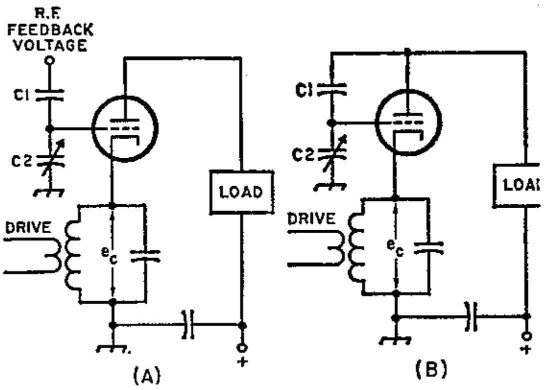


Fig. 7—Plate-circuit feedback. (A) Auxiliary control voltage may be applied to the grid of a cathode-driven stage, either in phase or out of phase with the driving signal. Capacitors C_1 and C_2 form a voltage divider, with grid voltage determined by setting of C_2. (B) Feedback voltage at grid of amplifier may be derived from plate signal, providing negative feedback and increasing drive requirements. Stage gain is decreased and rectified drive-power level is increased. As feedback level is increased, stage must be reneutralized.

watts). The nominal drive requirement of four cathode-driven 811A's is about 50 watts without additional feedback. Sufficient feedback is introduced by the choice of capacitor C_2 to raise the drive requirement of the amplifier to about 100 watts. At the same time, a reduction in intermodulation distortion of about 3 decibels is achieved. The feedback voltage is derived from the plate circuit as shown in Fig. 7B.

It should be noted that use of the grid element of the cathode-driven stage for auxiliary signal injection tends to upset the neutralizing balance of the stage to a degree. This may not be too important with well-shielded tubes used below 30 megacycles, but can become important in the lower reaches of the v.h.f. spectrum. As the power gain of the stage is reduced by decreasing the value of C_2 in Fig. 7, the neutralizing circuit (if any) must be rebalanced for minimum intrastage feedback.

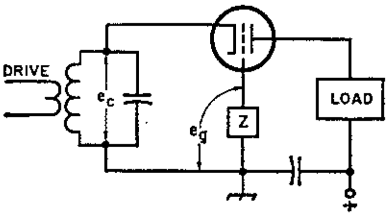


Fig. 8—Grid impedance in cathode-driven amplifier. General case for semi- and super-cathode driven amplifiers is summarized by placement of impedance *Z* in grid return. Magnitude and sign of *Z* determine stage gain, converted drive power, and total drive power. For average tubes in h.f. region, *Z* is usually positive (inductive), making the stage somewhat easier to drive than normal, and also making stage prone to instability and oscillation when external feedback circuits are not controlled. Feedback current (Iz) flows through grid-plate capacitance.

Effect of Grid Impedance

Both the semi-cathode-driven and super-cathode driven circuits may be summarized in the general case shown in Fig. 8, where an impedance Z is placed between grid and ground. Amplifier operation is assumed to be below the self-neutralizing frequency of the tube. It can be shown that when Z is positive (inductive) the amplifier is in a semi-cathode-driven mode and (as compared with a simple cathode-driven amplifier) requires a lower-than-normal value of driving power and exhibits less-than-normal converted drive power. On the other hand, when Z is negative (capacitive) the amplifier is in a super-cathode-driven mode, requiring a higher-than-normal value of driving power and exhibiting more-than-normal converted drive power. An example of an 811A cathode-driven amplifier having both zero and negative grid-impedance characteristics is shown in Table II. The magnitude and sign of Z, therefore, set the stage for operating parameters of the seemingly simple "grounded-grid" amplifier. Practical limits to the manipulation of impedance Z exist, as large values of impedance prevent effective neutralization of the cathode-driven stage.

Envelope-Modulation Circuits

A number of unorthodox linear amplifier circuits have come into vogue in the past decade (the "ZL-linear," the "Class C" linear, the "G2DAF" linear, etc.), all of which utilize some form of envelope modulation. A subsequent article will deal with these interesting circuits.

The authors wish to thank W. H. McAulay, W6KM and Raymond Rinaudo, W6KEV, for their assistance in the preparation of this article.

amateur service newsletter
W6SAI

The 3-500Z in Amateur Service

Here's a new zero-bias triode from Eimac that features increased plate dissipation.

The 3-500Z is a heavy-duty power triode of 500 watts plate dissipation. It is exceptionally well suited for use as a class-B amplifier in rf or audio application. It may be used in zero-bias linear-amplifier service at plate potentials up to 3000 volts, eliminating bulky and expensive screen and bias power supplies.

Of particular interest to the radio amateur is the use of the 3-500Z as a grounded-grid (cathode-driven) amplifier for ssb service. One 3-500Z is capable of a PEP input of over 1100 watts, requiring only 30 watts PEP drive power. Intermodulation distortion products at this power level are 30 dB or more below one tone of a two-tone test signal. At 2000 volts, moreover, over 500 watts of power output are obtainable with distortion products better than 38 dB below one tone of a two-tone signal. Typical operating characteristics for the 3-500Z are listed in **table 1.** A data sheet covering operation of the 3-500Z may be obtained at no cost by writing to me.

In cases requiring additional plate dissipation, the 3-500Z may replace the 3-400Z. The forced-air requirements for the two tubes are approximately equal and a blower capable of 13 cubic feet per minute at a back pressure of 0.2 inch is satisfactory for a single 3-500Z. (Use blower size #3 at 1600 rpm. For two 3-500Z's, use blower size #3 at 3100 rpm, or size #2½ at 6000 rpm.)

The zero-signal pate current of the 3-500Z is somewhat higher than that of the 3-400Z. When the 3-500Z is used to replace the 3-400Z, a means of reducing the zero-signal plate current is recommended, particularly if the equipment is power-supply limited. Only a few volts of bias from a low impedance source are required. The simplest way of obtaining well-regulated bias voltage is to place a zener diode in the filament return circuit of the 3-500Z **(fig. 1).**

The 1N4551 zener diode has a nominal voltage drop of 4.7 volts and an impedance of 0.1 ohm, making it ideal for this service. At this value of bias, the zero-signal plate current of the 3-500Z at a plate potential of 3250 volts is reduced from 160 to approximately 90 milliamperes.

The zener diode may be bolted directly to a cool area of the chassis which will act as a heat sink. Additional VOX-selective bias may be placed in series with this zener diode to reduce standby current of the 3-500Z to nearly zero in order to eliminate "diode noise" during reception and conserve standby power **(fig. 2).**

the grid-current meter

It is advisable to monitor the grid current of the 3-500Z as an indicator of correct drive and antenna loading. Too much grid current indicates underloading or overdriving and too little grid current indicates underdriving or overloading, other things being equal. As the grid must be held at rf ground, the grid meter must be introduced in such a manner as not to disrupt this circuit. A simple grid meter scheme is shown in **fig. 1.** Each grid pin is grounded through a .01-pF mica capacitor paralleled with a 3.3-ohm, 2-watt composition resistor. A small dc voltage drop exists across the resistor under normal tube operation. The voltage drop is read by a simple dc voltmeter (M1) calibrated in terms of grid current.

In the example shown, it is desired that the grid meter have a full scale indication of 200 milliamperes. The dc grid-to-ground resistance is about 1.1 ohm and, at a current of 200 mA, a voltage drop of 0.22 volts will be developed. The 0-1 dc milliammeter is converted to read 0.22 volts full scale by the inclusion of a series multiplier resistor. The sum of the resistor plus the meter resistance should total 220 ohms.

3-500Z circuitry

No specific circuits are shown for the 3-500Z, since published 3-400Z circuitry applies equally well to this tube. Two 3-500Z's may be used in place of a single 3-1000Z with appropriate corrections in air flow, filament power requirements and zener bias (if necessary).

ham radio

table 1. Typical operation of the 3-500Z in grounded-grid rf linear-amplifier service.

DC plate voltage	3000	2500	2000	V
Zero-signal dc plate current	160	130	95	mA
Single-tone dc plate current	370	400	400	mA
Single-tone dc grid current	115	120	130	mA
PEP input power	1110	1000	800	W
PEP useful output power	750	600	500	W
Resonant load impedance	5000	3450	2750	ohms
Cathode input impedance	115	100	100	ohms
Intermodulation products (3rd order)	—30	—33	—38	dB

fig. 1. Zener diode bias circuit for the 3-500Z. A 1N4551, 4.7-volt, 50-watt zener diode provides cathode bias for the 3-500Z. Meter M1 (0-1 mA dc) reads grid current of the tube in terms of the voltage drop across the three grid resistors. Meter M2 reads plate current. The multiplier resistor plus internal resistance of meter M1 should total 220 ohms. Grid and filament bypass capacitors are 600-volt mica units (M). Other bypass capacitors are ceramic discs.

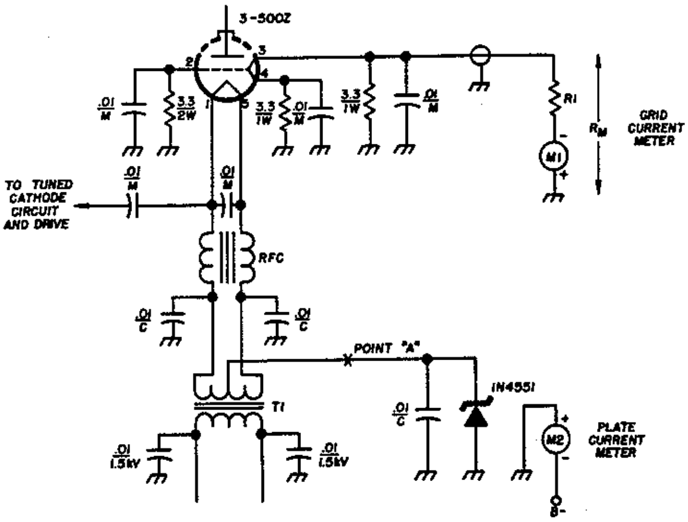
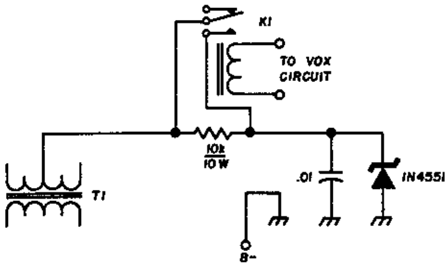
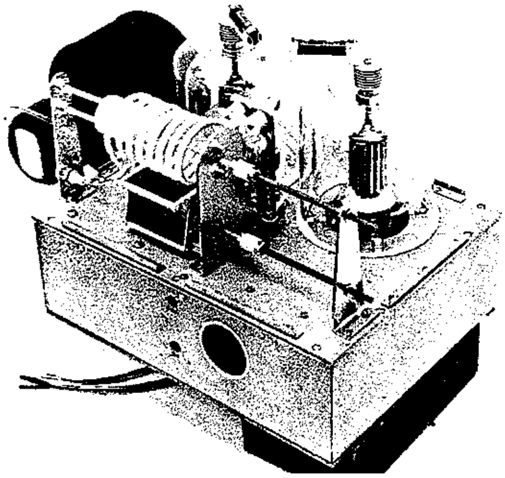


fig. 2. VOX-selective cutoff bias circuit. Additional cutoff cathode bias is added by the VOX relay to reduce standby plate current to near-zero, eliminating "diode noise" in a nearby receiver. The bias is added at point A in fig. 1.



amateur service newsletter
W6SAI



inductively-tuned high-frequency tank circuit

A method for achieving high efficiency in the "shadow region" between 14 and 54 MHz

William I. Orr, W6SAI, Eimac Division of Varian

Radio frequency amplifiers require a certain critical value of plate circuit impedance and Q for optimum performance at any frequency. Design deviations may lead to higher levels of intermodulation distortion or excessive harmonic radiation. While the design requirement may be quite tolerant in some cases, the mechanical assembly of the components and the choice of proper values become increasingly critical as the operating frequency nears the upper region of the hf spectrum. It is as though a "shadow region" exists that's too high for conventional lumped circuit components, yet is too low for conventional vhf linear and stripline techniques. The "shadow region" extends roughly from 27 through 54 MHz.

Above 27 MHz or so, the construction of a conventional high-power plate-tuning circuit having good Q and good efficiency can be vexing, as residual tube and circuit capacitances combine to assume a major portion of the tank circuit capacitance. It's possible, in fact, for this residual capacitance to be much larger than specified for proper design considerations. The unusually high circuit capacitance may lead to unreasonable Q and high circulating tank current, resulting in poor over-all efficiency and excessive heat loss in the tank circuit.

inductive tuning

To achieve good circuit efficiency and proper Q in the upper portion of the hf spectrum, it is convenient to resort to a different mechanical configuration than is commonly used at lower frequencies. One way to overcome problems of efficiency and Q is to reduce residual circuit capacitance to an absolute minimum by removing the cause of the largest portion of this unwanted capacitance: the tank tuning capacitor. Circuit resonance can then be established by including a fixed capacitance combined with a variable inductor.

The inductor can be a fixed, high-Q coil having a low-loss shorted turn introduced into one end. As the turn is moved within the coil, coil inductance is reduced, and resonance is established by correctly positioning the shorted turn **(fig. 1)**. The rf current in the shorted turn is high compared to the coil current; however, if the turn is of homogeneous structure and low-resistance material, turn losses will be small.

Shown in the photographs is a commercial 5-kW input PEP linear amplifier designed for any 500-kHz range between 27 and 54 MHz. The plate tank is a conventional pi network, inductively tuned by a shorted turn within the plate coil. The turn (or "slug") is moved into and out of the coil by a lead screw driven from a counter dial mounted on the amplifier panel. Tank circuit values were derived from pi network charts.[1]

The amplifier uses a pair of parallel-connected 3-1000Z high-mu triodes in a grounded-grid, cathode-driven circuit with zener diode bias.[2] The combined output capacitance of the tubes is approximately 15 pF. Stray circuit capacitance from plate to ground is less than 10 pF, which provides a minimum input capacitance (C1) for the pi network of about 25pF. Additional capacitance can be added for operation at lower frequencies. Ceramic or vacuum padding capacitors can be used for this purpose.

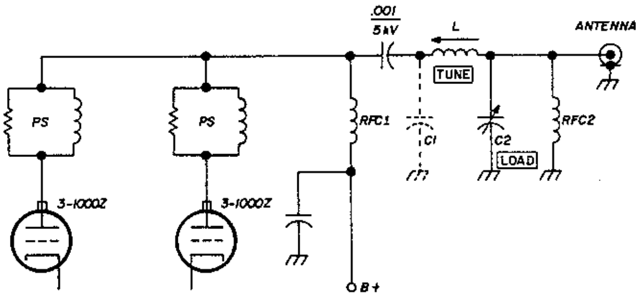


fig. 1. Inductively tuned tank circuit using conventional component values. C1 is the residual circuit capacitance plus tube output capacitance. Resonance is achieved by a variable shorted turn moved inside L.

construction

Tank-circuit inductance is calculated for the low-frequency end of the tuning range in the usual manner. As the shorted turn is driven into the plate inductor, its inductance decreases, and resonant frequency increases. A range of about 500 kHz or so can be obtained with this assembly.

Construction details are shown in **fig. 2.** The shorted turn is a section of seamless copper water pipe 1-¾ inches O.D. by 3 inches long. Discs of insulating material are cut to fit into the ends of the pipe and are held in position with small pins or rivets. A

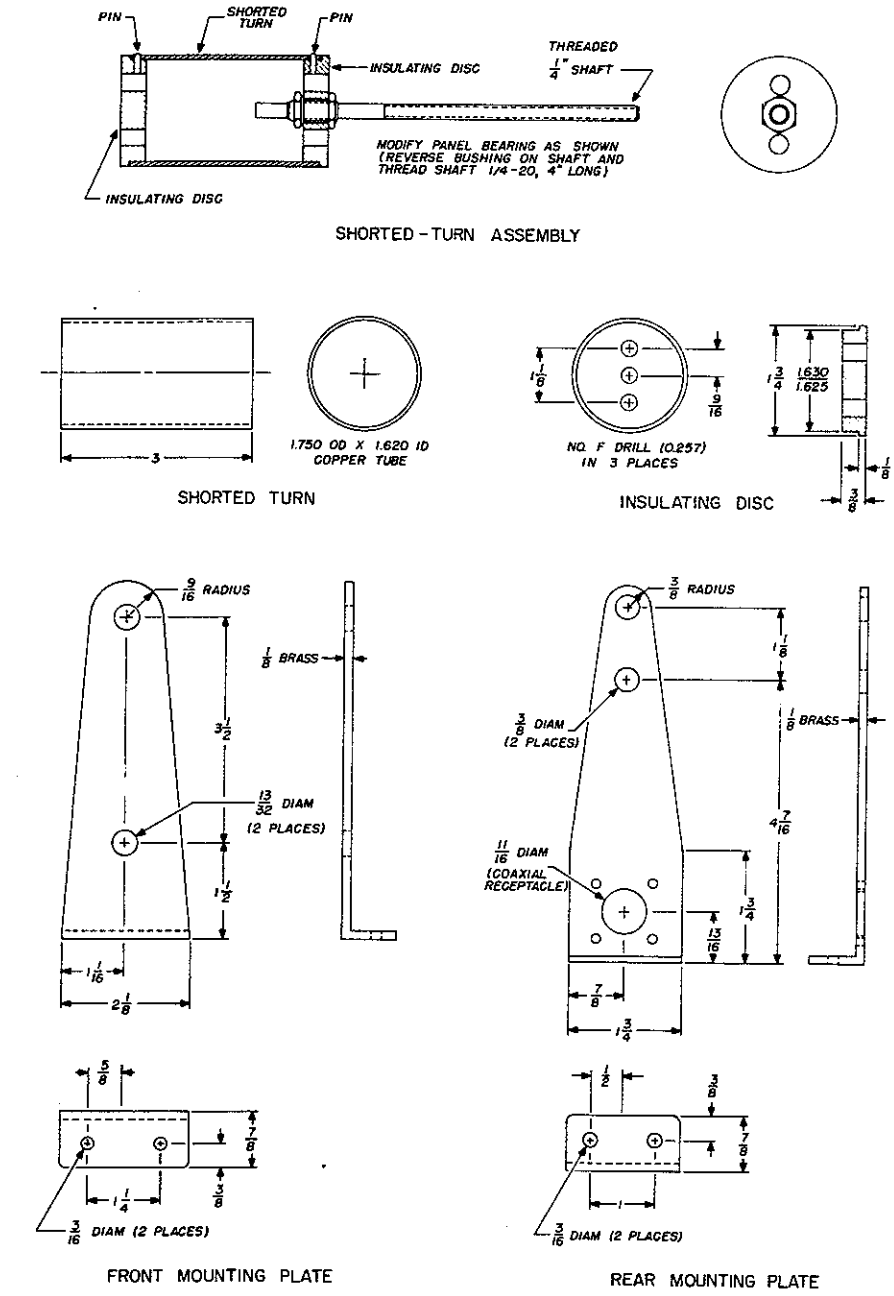
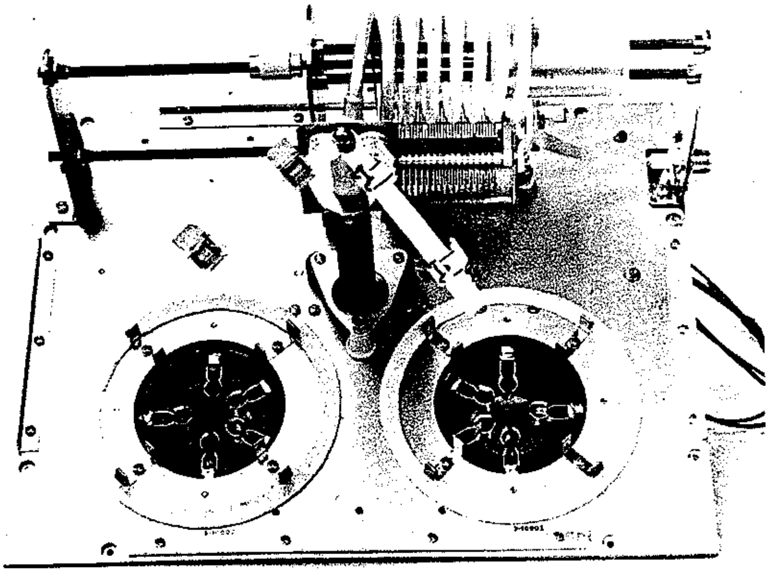


fig. 2. Mechanical details of the shorted-turn assembly.

threaded bushing is attached to one disc, through which the drive shaft extends. The shaft is ¼-inch-diameter copper rod, threaded with a ¼-20 die. Two fiberglass guide rods are mounted between the end support brackets to keep the shorted turn from rotating as it's driven back and forth. The threaded drive shaft is driven from the amplifier panel by an insulated extension shaft and an insulated coupling. The shorted turn is ungrounded at all times, and no moving parts carry rf current.

The plate tank coil is wound with ¼-inch-diameter silver plated copper tubing with an I.D. of 2-¼ inches, providing ample clearance for the shorted turn to move within the coil without danger of arcing. Heavy-duty copper mounting lugs are silver soldered to the coil. Resonance is initially established with a grid-dip oscillator. Indication of resonance is quite broad. Loading is accomplished with the pi network variable output capacitor, C2.



top view of the high-power commercial amplifier. Inductively tuned tank is shown at rear. Tuning is the same as with a variable capacitor, except inductance decreases as shorted turn penetrates coil. Parasitic suppressors have been removed for this photo.

parasitic suppression

An important consideration in plate-circuit design is a parasitic suppressor. In this amplifier parasitic suppressors are included in each plate lead. Each suppressor is a 40-ohm, 16-watt *Glo-bar* resistor shunted across an inductor, which consists of a length of plate lead. The value of the shunt inductance is important. A too-small value won't completely suppress the tendency for vhf parasitics, and a too-large value will cause excessive fundamental rf power to dissipate in the parasitic resistor. The proper value of shunt inductance, while not particularly critical, should be determined for the operational range of the amplifier in each case.

The amplifier shown in the photographs was designed for commercial service and is included in a shielded cabinet as part of a larger package. A similar design using 4-1000A's has been built for commercial ssb service at the 6-kW PEP level—but that's another story. The basic design is adaptable to any high-power amplifier operating in the upper region of the hf spectrum.

references

1. William I. Orr, "Pi and Pi-L Networks for Linear Amplifiers," *ham radio,* November, 1968, page 36.

2. William I. Orr, "The 3-500Z in Amateur Service," *ham radio,* March, 1968, page 56.

ham radio

amateur service newsletter
W6SAI

intermittent voice operation of power tubes

William I. Orr, W6SAI, EIMAC Division of Varian, San Carlos, California 94070

The power capability of a transmitting tube is often the subject of long and heated discussions among amateurs (and even among equipment design and tube engineers). In the past, amazing things have been done to power tubes by daring amateurs who seemingly had an inexhaustible supply of replacement tubes at hand.[1] The tube manufacturer looks upon such goings-on with mixed emotions; he's proud his products can take such a beating, but he shudders at the gross overload he knows is taking place, and he has nightmares when he imagines that such tactics are being done by users who may be ignorant of the basic limitations of vacuum tubes. Sometimes that manufacturer may be his own worst enemy. When he speaks of the ruggedness, long life and reliability of his product, he may unintentionally be inviting some eager-beaver to prove the utter conservatism of his remarks.

Up to now, tube ratings have been based upon an absolute system providing "maximum" ratings and "typical" operating conditions for various classes of service, for use below a certain specified frequency. These ratings are designated as *Continuous Commercial Service* (CCS) and *Intermittent Commercial and Amateur Service* (ICAS). The CCS rating may be defined as, "that type of service in which long tube life and reliability of performance under continuous operating conditions are the prime consideration.[2]" The ICAS rating is defined to include the many applications where the "transmitter design factors of minimum size, light weight, and maximum power output are more important than long tube life." The term "intermittent" is used to identify operating conditions in which no operating or "on" period exceeds five minutes and every "on" period is followed by an "off" or standby period of at least the same or greater duration.

These ratings are of cold comfort to today's radio amateur. The first rating applies to high-reliability service (broadcast, military, etc.) wherein off-the-air time is critical or costly; and the second rating, by its very definition, excludes amateur operation in meaningful terms. Neither classification, moreover, applies to ssb or cw operation. Ssb and cw are more properly expressed in terms of peak-to-average power ratio rather than in terms of "on" and "off" periods.

Before new and meaningful ratings are proposed for today's operational modes, it would be prudent to look for a moment at transmitting tube ratings now in use and examine their validity. Contrary to often expressed belief, maximum ratings and typical operating conditions are not arbitrary figures dreamed up by the manufacturer to avoid answering legitimate questions posed by users. On the contrary, they are the result of careful analysis of tube geometry and of prolonged life tests run on typical production tubes with some guaranteed or expected life in mind. Properly understood, the maximum ratings and typical operating conditions can be employed by the tube user to decided advantage.

transmitting tube ratings

Maximum ratings (or absolute maximum ratings) are those limits within which all tubes of a given type should give satisfactory service and long useful life. Why they are necessary at all and how they are determined are discussed in this article.

The *data sheet* (often suspected of being written by the wise to impress the humble) informs the user of the capabilities and limitations of the tube, both of which are based upon the maximum temperature the elements of the tube can safely withstand for an expected life. Heat, then, is the enemy of unlimited tube life, but heat is the unfortunate consequence of making the tube work. Once the maximum tube capability is determined *a compromise of some kind must be made to establish useful life without exceeding the heat limitations, yet allowing some safety factor for "cockpit troubles."*

maximum plate dissipation

Plate dissipation is limited by the maximum safe temperature of the plate and plate-to-glass (or ceramic) seals of the tube. Generally speaking, the plate will withstand several times its maximum rated dissipation level for a short period of time. Other parts of the tube (glass envelopes, mainly) are greatly affected by the excessive heat radiated by the plate. High level of plate temperature may cause the grid, filament or envelope to become overheated. The grid structure may warp, the filament temperature may rise to an excessively high degree, or the tube envelope may be destroyed. These effects, however, are not instantaneous, and short periods of plate overload do not usually overheat the adjoining tube structure to a damaging extent. However, the user has no way of telling to what degree he can safely exceed the plate dissipation limit, or over what period of time this abuse can take place. The obvious conclusion is that the maximum plate dissipation rating should not be exceeded in continuous operation if long tube life is desired.

maximum plate voltage

The maximum plate voltage point is set at a value above which the internal or external insulators of the tube may arc over, or above which the envelope of a glass tube may be damaged from dielectric losses. Finally, a plate voltage ceiling tends to set a limit to the maximum rf charging current flowing in the plate and screen leads, or plate and grid leads in grounded-grid service. The charging current is a function of the rf plate voltage which, in turn, is a function of the dc plate voltage. Setting a limit on the dc voltage sets a limit on charging current without the difficult task of determining the current directly. This effect depends on frequency and is the reason for the upper frequency limit for maximum ratings.

average dc plate current

The fundamental limit on plate current is the available supply of electrons emitted by the filament or cathode of the tube. The maximum plate-current figure is intended to set a value which may be easily realized throughout the expected life of the tube. If operating conditions are chosen which require that the maximum plate-current limitation to be exceeded at the start of tube life, it may become increasingly difficult to maintain the desired value of plate current as the tube ages. There is a definite relationship between the *maximum instantaneous value* of plate and grid current and the *average dc* (meter reading) *plate current* which differs for each class of tube operation. In linear-amplifier service, for example, most transmitting tubes are run class AB_1, AB_2 (loosely termed class B).* In these cases, the peak plate current is about three times the indicated (average)

*Most class-B linear amplifiers are operated in class AB_2. Class-B operation is defined as cutoff operation with an 180° operating angle of plate current flow. Class AB_2 operation signifies less-than-cutoff condition with more than 180° operating angle.

dc plate current. For long life, the cathode emission should be great enough to provide two or three times the required peak value of plate, plus grid, plus screen current.

The user can quickly determine the allowable average dc plate current in linear service for thoriated tungsten filament-type tubes by merely multiplying the filament watts by a factor of about 5.5. This is a rule-of-thumb number that — over the years — has proven to give a conservative balance between allowable plate current and good tube life. For the 3-500Z, therefore, the filament power is 5 (volts) x 14.5 (amperes) = 72.5 watts. Therefore, allowable maximum average dc plate current for linear amplifier service is 72.5 x 5.5 = 400 milliamperes.

In the case of an indirectly heated cathode the rule-of-thumb is different. Emission from an indirectly heated cathode depends upon the emissive material and the active cathode area, assuming cathode temperature is the proper value. The rule-of-thumb in this case for oxide cathodes is that maximum average dc plate current is approximately 125 milliamperes for each square centimeter of cathode area. For example, the 4X150A tetrode has an active cathode area a little over 2.0 square centimeters and the average dc plate current rating is 250 milliamperes.

long pulse service

In pulse service where the "on" time is small compared to the "off" time, many transmitting tubes can be run to much higher peak power limits than are permissible in continuous service. In continuous service, the maximum voltage and current limitations are set with a safety factor in mind to consider average power dissipated on the tube electrodes. In pulse service, when the tube "rests" for an appreciable time, it is possible to set new guidelines on peak electrode dissipation and maximum ratings, provided the *average* electrode dissipation and maximum temperature ratings are not exceeded.

In pulse service (less than 0.1 second) a thoriated tungsten power tube may have an anode instantaneous peak dissipation capability as high as 100 times the average power capability, and the available filament emission may be as high as 80 milliamperes per watt of filament power. In some cases, the filament voltage has been boosted above normal to obtain emission levels as high as 150 milliamperes per watt with the penalty of greatly reduced tube life.

In the case of the oxide-coated cathode, the peak pulse current is not as clearly defined or as easily generalized as in the case of the thoriated filament tube. A figure of 500 milliamperes peak plate current per watt of heater power is often used for very short pulse service (less than 3 microseconds), and other numbers are available giving pulse plate current in terms of active cathode area.

In *long* pulse service (more than 0.1 second), the rise in temperature of the electrodes rather than the average power during the pulse often becomes the basic tube limitation, and twe maximum capability of the power tube is progressively derated as the pulse length increases. For a radiation cooled tube, a pulse length of 2.5 seconds is often considered equivalent to a continuous duty operation. In the case of an oxide-coated cathode, life tests indicate that a peak-to-average dc plate current ratio of 2.0 for long pulse (0.5 second) is not unrealistic. This corresponds to a duty factor of 0.5.

voice and cw operation

A shadow world exists between continuous duty (CCS) operation, and ICAS operation on the one hand and pulse operation. Amateur voice and cw operations seem to fall into this shadow area. Cw operation may be compared to a form of pulse operation as it defines an "on" and "off" duty cycle wherein the two times are approximately equal. This would represent a duty cycle of fifty percent (0.5) and the pulse (cw) waveform would be nearly square.*

---

*Note quite true; waveshaping is necessary to some extent to reduce key clicks.

Voice operation, on the other hand, is a different and more complex problem. The voice waveform is not a square pulse; it has a large peak-to-average power ratio with irregular waveform. Normal speech, unclipped, uncompressed or otherwise altered, seems to have a peak-to-average ratio of about 14 dB.[3] Various compression and clipping techniques can reduce this ratio to 3 to 5 dB before severe distortion becomes apparent.[4] Thus, heavily clipped or compressed speech waveforms tend to resemble the cw duty cycle as far as the peak-to-average power ratio is concerned.

It is prudent to expect, therefore, that the power capability of a tube can be safely increased for *Intermittent Voice and CW Service* (IVS service) over the CCS rating provided the maximum element temperature of the electrodes is not exceeded and the cathode (or filament) emission is sufficient to satisfy plate and grid current peaks. In addition, the tube in question should not have an intolerable level of intermodulation distortion when operated in linear service under these enhanced conditions.

This type of intermittent operation is done everyday with the popular sweep tubes used in ssb equipment designed for amateur service. Small soft-glass envelope tubes (i. e., the 6LQ6) are run up to 250 or 300 watts PEP input with no apparent harm *provided* the maximum level of plate dissipation is held within reason, even though the average, long-term dissipation rating in tv service is only 30 watts or so. The user is taking advantage of the intermittent nature of amateur voice operation and the high peak-to-average ratio of the human voice to get more watts per dollar of tube investment. Many amateurs have found, to their regret, an overworked sweep tube tends to overheat and shows extremely short life when a voice clipper/compressor unit is used to bring up the average power of the equipment, or if extended cw operation is used. A moment's reflection upon the heating process in the tube will show the reason for this problem. The tube is being pushed so far that any margin of safety has vanished. Unfortunately, no one has yet been able to miniaturize the watt!

Thus, there's a limit beyond which pushing the transmitting tube becomes uneconomical. It may be well to push an inexpensive sweep tube to 300 watts PEP input, since a tuning error, or other maladjustment won't bankrupt the unlucky user. The owner of a more expensive transmitting tube, however, may well have second thoughts before he blasts his pet power tube. Obviously, some middle ground is called for where the peak-to-average power ratio of ssb and cw operation can afford new and conservative tube ratings more in line with today's usage.

intermittent voice service

In single sideband service, the two plate current values of significance are the single-tone plate current and the two-tone plate current. The ratio of single-tone to two-tone plate current may vary from 1.1/1 to 1.57/1, depending upon the class of operation. Two-tone plate current is useful as the magnitude of intermodulation distortion products may be specified as the reduction in decibels of one product from one tone of a two-equal-tone signal. Precedence exists, therefore, for providing typical operating data for linear amplifier service specifying the dc plate current under two-tone conditions of average plate current and plate current at the peak of the modulation envelope. Such data for the 8122 is shown in **table 1.**[2]

Based upon such data, extensive life tests have been run at the Eimac Division of Varian to determine if more meaningful operating conditions could be specified for either ssb or cw operating modes. As far as amateur operation is concerned, the limiting mode is cw, where the duty factor is about 0.5. The duty factor for single sideband transmissions with unprocessed speech runs about 0.05 for a 13-dB peak-to-average signal and could rise as high as 0.5 for high levels of speech compression or clipping. A duty factor of 0.5 (peak-to-average ratio of 2.0) for Intermittent Voice Service rating would therefore cover both table 2. Preliminary operating data for 8873 family of ceramic/metal, zero-bias power triodes.

Cathode: Oxide coated, unipotential	
Warm-up time	60 sec
Heater voltage	6.3 V
Heater current	3.2 A
Direct interelectrode capacitances, grounded-grid connection	
Input	19.5 pF
Output	7.00 pF
Feedback	0.04 pF
Maximum frequency ratings	450 MHz
Operating temperature, maximum, ceramic seals and anode core	250° C
Base	11-pin Special (JEDEC E11-81)
Radio-frequency linear amplifier, cathode driven, class AB_2	
Absolute maximum ratings, to 450 MHz	
Plate voltage	2200 Vdc
Plate current, continuous	250 mA
Plate dissipation	see note 1
Grid dissipation	5 W
Typical operation, Intermittent Voice Service[2] frequencies to 30 MHz	
Peak envelope or modulation crest conditions	
Peak voltage	2000 Vdc
Cathode voltage[3]	8.2 Vdc
Zero-signal plate current	22 mA
Single-tone IVS plate current	500 mA
Two-tone plate current (approximate)	312 mA
Average plate current	250 mA
Single-tone grid current	30 mA
Two-tone grid current	12 mA
Peak rf grid-cathode voltage	67 V
Peak driving power	26 W
Peak power input	1000 W
Single-tone IVS useful output power	587 W
Resonant load impedance	2140 ohms
Intermodulation distortion products:	
3rd Order	-35 dB
5th Order	-36 dB

notes. 1. 8873 is conduction cooled, and plate dissipation depends upon heat-sink cooling. 8874 plate dissipation is 400 watts, and tube has an axial-flow, forced-air cooled anode. 8875 plate dissipation is 300 watts, and tube has a transverse-flow, forced-air cooled anode.

2. Intermittent voice and cw ratings are based upon the maximum voltage and current ratings given for a signal having a peak-to-average power ratio of 2.0 or more. During short periods of adjustment (less than 30 seconds), the average plate current may be as high as the IVS value.

3. Cathode bias is obtained from a zener diode.

the cw and ssb speech-with-processing situations.

The derivation of a different rating from an existing rating may only take place after extensive life tests have been completed to make sure that tube life is not being shortened and that maximum temperature and dissipation limits are not

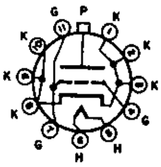


fig. 2. Tube base diagram for the 8873, 8874, 8875 family of zero-bias triodes. Multiple cathode leads keep cathode inductance to a minimum.

being exceeded. Any tube may be limited by grid or screen dissipation level and some may be limited by a plate voltage ceiling, or by available cathode emission. *Each tube type is an individual case, and to jump to conclusions or to interpret data from one type to another is risky and unfounded to say the least.* In all cases the total average current load on the oxide cathode will remain about the same for the new rating as for the average situation.

The *Intermittent Voice and CW (IVS)* rating may be defined as:

> That maximum voltage and current rating given for a signal having a maximum peak to average power ratio of 2.0 or more. During short periods of adjustment (less than 30 seconds), the average plate current may be as high as the IVS value.

In all cases, the IVS rating and "short period of adjustment" are limited by the maximum allowable temperature of the tube anode and seals.

using the ivs rating

The IVS rating is especially attractive to amateur operators as it outlines typical operating parameters for cw and ssb. How are the new ratings used? The following is an example of how an amateur operator can safely and properly tune up for an IVS operating condition with the aid of an inexpensive oscilloscope.

The oscilloscope is necessary for ssb adjustment at first since meter response to a voice waveform may vary from meter to meter and is, in any case, highly irregular and difficult to interpret.

1. The first step to achieve an IVS condition for either ssb or cw is to tune and load the linear amplifier with carrier (single tone) to an IVS rated value of dc plate current (as read on the plate meter), observing maximum "on" time. The amplifier is now ready for IVS CW operation. This could be called the "long-dash" tuning method. An electronic key is handy for this operation.

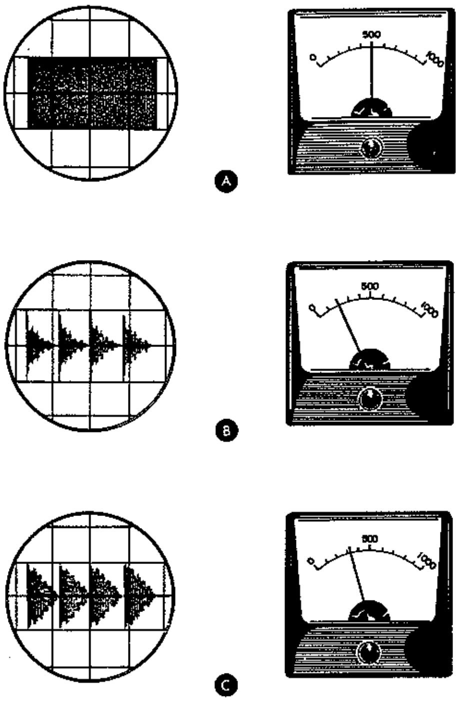


fig. 1. Typical meter readings for IVS operation.

A. With single tone (carrier), the linear amplifier is loaded to maximum IVS plate current (500 mA in this example). Oscilloscope shows carrier pattern. Pattern height is noted as 2 units. Observe short tuneup time.

B. Carrier is removed and voice modulation applied and gradually increased until voice peaks reach carrier height of 2 units as noted in pattern A. Plate meter kicks up to about 200 mA on voice peaks. No speech processing used.

C. Adding speech processing (clipping or compression). Note that plate meter now kicks up under voice peaks to about 325 mA, but that voice peaks on oscilloscope rise no higher than the single-tone limit of 2 units. However, area under the peaks is greatly enhanced, indicating greater average-to-peak ratio of voice signal. If oscilloscope peaks are greater than 2 units height, with or without voice processing, amplifier is being overdriven, with accompanying splatter and distortion.

2. For ssb observe the rf output pattern on the oscilloscope and note the amplitude for reference.

3. Remove the carrier. Insert audio and slowly increase audio gain so that the instantaneous rf peaks observed on the oscilloscope reach the same maxi-

table 1. Type 8122, linear rf power amplifier service (AB_1). Typical CCS operation at 30 MHz with two-tone modulation.

Plate voltage	**2000 Vdc**
Grid no. 2 voltage	**400 Vdc**
Grid no. 1 voltage	**-35 Vdc**
Zero-signal plate current	**100 mA**
Plate current	
Peak of envelope	**335 mA**
Average	**250 mA**
Grid no. 2 current	
Peak of envelope	**10 mA**
Average	**7 mA**
Average grid no. 1 current	**0.05 mA**
Effective rf load resistance	**3050 ohms**

mum level as obtained in *step 2* under carrier insertion. The amplifier is now working at the correct IVS level of peak input.

4. Observe the average current peaks on the plate meter for future reference.

In summary, the amplifier is tuned up to IVS condition with single-tone excitation to set the peak signal level. The single tone is removed, and audio is applied so the instantaneous signal peaks reach the same peak level as before, but the peak-to-average level of the intelligence may vary widely, depending upon voice characteristics, degree of speech processing, etc. This is summed up in fig. 1.

ivs ratings for the 8873 family of triodes

The new 8873 family of zero-bias triodes is the first to carry the new IVS rating. These ratings are based upon the original design concept of the tube, plus extended life tests where electrode temperatures, cathode emission and power output were carefully monitored. For example, the continuous plate current rating is 250 milliamperes. The cathode area of the 8873 is over 2 square centimeters; this corresponds quite closely to the 125 milliamperes per square centimeter rule-of-thumb stated earlier for an oxide-coated cathode. The life tests showed that a peak dc plate current rating of 500 milliamperes is reasonable at a duty cycle of 0.5 (peak-to-average power ratio of 2.0), corresponding to the IVS philosophy (**table 2**). The various input levels at a given plate voltage may now be established. At 2000 volts, for example, the average plate input is 2000 (volts) x 250 (milliamperes) = 500 watts. This corresponds to key-down service, such as RTTY. The two-tone rating (as in a short two-tone test) is 2000 (volts) x 312 (milliamperes) = 624 watts, average power. The IVS rating for ssb voice or cw is 2000 (volts) x 500 (milliamperes) = 1000 watts peak envelope power. In the case of voice and cw, the average current "load" on the cathode is the same.

Thus, today's power tube may be rated in two different and useful ways. Commonly, it bears the continuous duty (CCS) rating, and occasionally it bears the semi-obsolete ICAS rating. It is hoped that the new IVS rating will find favor in the future as it permits greater operating economy to be achieved in the use of all power-grid tubes.

what about . . .

The immediate question arises, "If this is so, what about the IVS ratings for the 3-500Z or the 8122 or the 4X150A, or whatever?" The present answer to this query is that *each tube type must be examined on its merits* and the outer limits established for any new rating, whether it be pulse, ICAS, or IVS. This is a continual process with most tube manufacturers, and more relevant date of this type will probably be forthcoming over the months.

Thanks to William McAulay, W6KM; Jack Quinn, W6MJG; and Robert Sutherland, W6UOV, for their help in the preparation of this article.

references

1. Perrine, "Thirty-Three Watts per Dollar from a type '52," *QST*, September, 1932.
2. RCA Electron Tube Handbook, HB-3, Volume 1, "Tube Ratings," RCA, Harrison, New Jersey 07029.
3. Magnuski and Firestone, "Comparison of SSB and FM for VHF Mobile Service," *Proceedings of the IRE*, December, 1956.
4. Collins, "Ordinary and Processed Speech in SSB Application," *QST*, January, 1969.

ham radio