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A 100-WATT POWER AMPLIFIER

By
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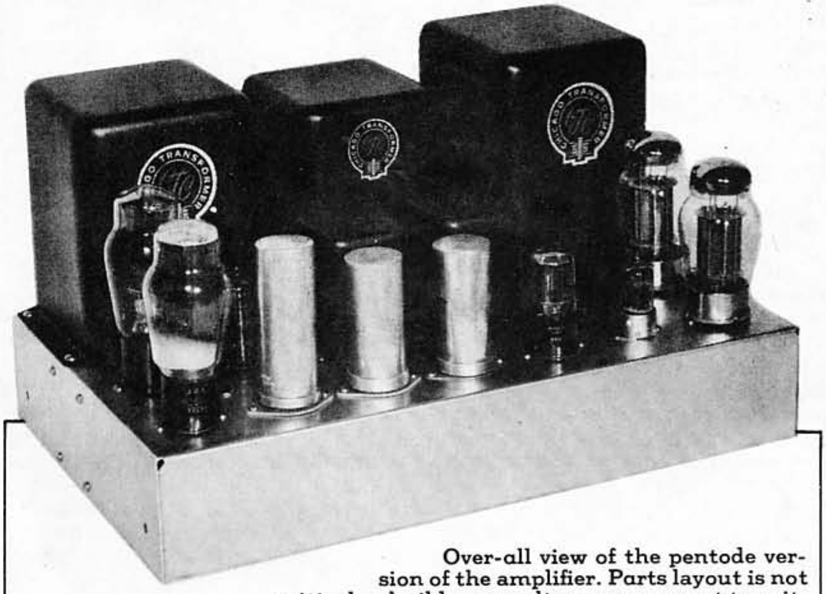


Over-all view of the pentode version of the amplifier. Parts layout is not critical so builder can alter arrangement to suit.

Details on a practical circuit which utilizes the special characteristics of the new Tung-Sol 6550.

HEARTS of audio designers were gladdened by *Tung-Sol's* announcement last year of the 6550 pentode, filling a long-felt need for an amplifier tube in its power class. Previously, tubes of this kind commonly used in American versions of the *Williamson* circuit did not fill the demand for a triode-connected output stage tube which could deliver the peak power requirements of a home installation at operating conditions well within the tube's maximum rating. The 6550 is rated to deliver 28 watts in the push-pull triode connection, which allows a safe reserve of power handling capacity for those who wish to design conservatively even for a large home installation. In pentode operation a pair of tubes will deliver 100 watts reliably.

Examination of the 6550 tube data given in Table 1 shows that the most unusual requirement is the large screen current swing between "no-load" and "full-load" conditions. For operation at the 100-watt output ratings, the current swing of 4 to 41 ma. is at the limit of what can be handled by VR tubes. In actual practice it would be unwise to use VR tubes because normal variations in line voltage to the amplifier power supply would very likely shift the current swing to a range that could not be handled by the VR tubes. Conservative design dictates the use of a separate 300-volt supply of good regulation. If we are to realize the 100-watt output at low distortion, a fixed bias supply is also required. By now the power supply problem alone looks formidable enough, on the grounds of complexity and cost, to discourage the 100-watt project. However, if a single power transformer could be obtained with all the necessary windings, the problem would be relatively simplified and much less expensive. Such a transformer is available as the *Chicago Standard* PCR-300, from which both screen and bias supplies can be taken through taps on the main high-voltage winding. The requirement of good regulation on the screen supply is met by a choke-input filter system, which fortunately happens to provide exactly the right voltage.

The same power transformer can be used for triode operation if the plate supply is changed from capacitor input to choke input, reducing the voltage to about 475. A unique feature is that a d.c. heater supply for a separate preamplifier can now be obtained from the bias supply taps without exceeding transformer current ratings.

Pentode Operation

To make the most of the high power output capability of the 6550, pentode operation at 600 plate volts along with fixed bias would seem sensible. A circuit along the lines of that made famous by Williamson no doubt would be highly satisfactory, but in order not to overlook other possibilities, several alternative circuits were investigated.

Some public attention has recently been focused on the use of push-pull feedback from the plates of both output tubes. If the feedback is applied to the driver cathodes, large amounts of feedback can be used without danger of oscillation. In a two-stage feedback system, oscillation cannot occur because phase shift will not reach the 180 degrees required for oscillation. Feedback in this case will reduce the phase shift as well as amplifier gain, thus making it easy to apply additional feedback around the output transformer and still maintain stability.

Bearing in mind that the distortion should be reduced by an amount equal to the feedback factor, it appears that an amplifier with lower distortion than the *Williamson* can be built because greater feedback can successfully be employed. This rosy outlook will receive a stiff jolt when an intermodulation distortion meter is used to measure the results of such designs. Different feedback circuit configurations were tried, all taken from both output tube plates, and none gave lower distortion than when feedback from the transformer output winding (á la *Williamson*) was used alone. The important factor of balance between both sides of the push-pull circuit was taken into account.

Rather than waste space with a detailed proof of these facts, let us look at the results obtained by a reputable manufacturer employing the foregoing techniques. A widely advertised amplifier on today's market uses push-pull feedback from the output tube plates plus feedback around the output transformer. The advertisement states that 36 db of feedback is employed and that the intermodulation distortion at full output is 1%. Now 36 db feedback is a 63 times reduction, and the initial amplifier distortion should be reduced this much. However, tubes of the 5881 class used here can have IM distortion as low as 4%[1] with no feedback. We can therefore expect 0.06% IM with feedback. The great discrepancy is due in large part simply to the use of the two kinds of feedback applied together as described, one of which is not wholly beneficial.

An attack on amplifier distortion may well be aimed at the output stage alone since by far the most distortion is introduced in this unit. Application of plate-to-grid feedback will not do, because aside from the question of whether or not distortion is materially reduced, we cannot tolerate reduction of the a.c. grid circuit impedance to the low values which will result with the 50,000-ohm maximum d.c. resistance specified by the manufacturer in this service. A more attractive method is to use a tertiary winding in series with the cathodes. This circuit, facetiously dubbed "super - ultralinear" by Williamson, has not enjoyed the popularity in this country that it deserves. With it, distortion levels lower than those obtained with triodes can readily be obtained.[2] The feedback used is 100% effective in reducing distortion and furthermore is fully compatible with feedback applied around the output winding. There is, however, a price to be paid. The driving voltage required on the output stage grid will be increased by the feedback factor. Since tubes customarily used as drivers are already called upon to deliver a voltage swing which approaches the limit to be expected for low distortion, we will reach a limit on the amount of feedback that can be judiciously applied. A further limiting factor acting against developing a high driving voltage is the low value of grid resistance required in this service. Hence the 6SN7 is ruled out and, on the basis of test results, the 5687 was selected. To secure the greatest possible voltage output at the lowest distortion, it is advisable to use the full plate supply voltage of the 6550's on the 5687. A considerable portion of the success of this amplifier is attributable to the large distortion-free grid driving voltage available from the 5687 tube at impedances which suit the 6550 grids.

To offset the disadvantage of added drive requirement we have an unusual bonus in the way of distortion reduction. Ordinarily, distortion is reduced by the feedback factor. That is, if feedback is applied reducing amplifier gain by 10 db, the distortion will be reduced 10 db. In the push-pull stage, local feedback applied in the manner described results in a double reduction in distortion. Ten db of gain reduction results in 20 db of distortion reduction or, in other words, the distortion is reduced by the square of the feedback factor and not by just the amount of the feedback factor. This fact seems to have been overlooked or ignored by some previous writers but well deserves emphasis since it is not common knowledge. It is probable that earlier investigators missed the point or failed to detect it because if only a small amount of feedback is used, the double reduction effect might not be recognized, for the square of a small number is not much greater than the number itself. Matters like push-pull imbalance and driver distortion could mask small gains in distortion reductions. It is not until larger amounts of this kind of feedback are applied that appreciable gains in distortion reduction can be measured to any degree.

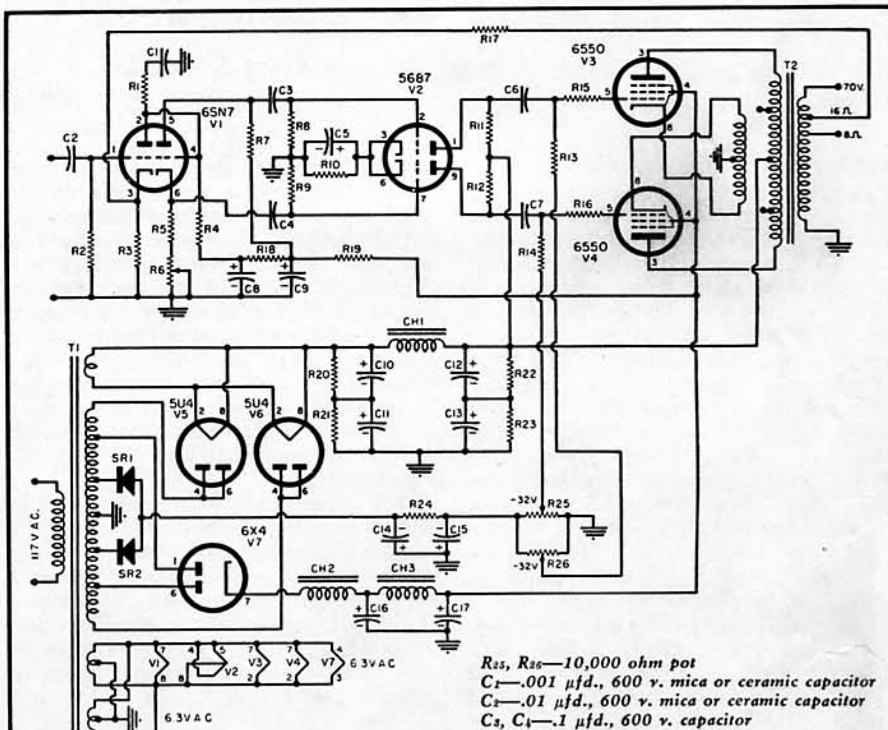
The output transformer selected was the new *Chicago Standard* "Super-Range" transformer developed especially for the 6550's and employing a tertiary winding designed to give the maximum practical feedback. IM distortion using only this type of feedback is under one per-cent. A moderate amount of feedback added around the output transformer will readily bring distortion down to levels so low that it is on or below the threshold levels which a conventional IM distortion meter can measure. It was established that 14 db of outside feedback is sufficient to

PUSH-PULL AMPLIFIER
(Values are for two tubes)

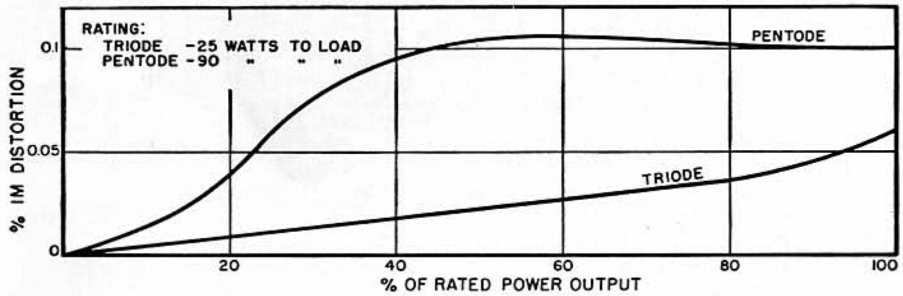
	Pentode			Triode	
	Fixed bias		Self bias		
D.C. Plate Voltage	400	600	400	450	volts
D.C. Grid No. 2 Voltage	275	300	300		volts
D.C. Grid No. 1 Voltage	−23		0	−46	volts
Cathode Resistor	——	——	140		ohms
Peak A.F. Grid-to-Grid Voltage	46	62	53	92	volts
Zero Signal Plate Current	180	115	166	150	ma.
Zero Signal Grid No. 2 Current	9	4	7.5		ma.
Maximum Signal Plate Current	270	273	190	220	ma.
Maximum Signal Grid No. 2 Current	44	41	39		ma.
Load Resistance	3500	5000	4500	4000	ohms
Power Output	55	100	41	28	watts
Harmonic Distortion	3	2.5	4	2.5	per-cent
Maximum Grid Circuit Resistance	50	50	250	250	kilohms

Table 1. Typical operating characteristics for the Tung-Sol 6550 tube.

The pentode version of the 100-watt amplifier using the new 6550 tubes.



R_1—3300 ohm, ½ w. res.
R_2—680,000 ohm, ½ w. res.
R_3—270 ohm, ½ w. wirewound res. (IRC Type BW-½)
R_4—47,000 ohm, 1 w. res.
R_5—12,000 ohm, 1 w. res.
R_6—5000 ohm pot ("Balance Adjustment")
R_7—15,000 ohm, 1 w. res.
R_8, R_9—1 megohm, ½ w. res.
R_{10}—470 ohm, ½ w. res.
R_{11}, R_{12}—25,000 ohm, 10 w. wirewound res.
R_{13}, R_{14}—56,000 ohm, ½ w. res.
R_{15}, R_{16}—2700 ohm, ½ w. res.
R_{17}—4700 ohm, 2 w. wirewound res. (IRC Type BW-2)
R_{18}—5600 ohm, 1 w. res.
R_{19}—3300 ohm, 1 w. res.
R_{20}, R_{21}, R_{22}, R_{23}—68,000 ohm, 2 w. res.
R_{24}—4700 ohm, 2 w. res.
R_{25}, R_{26}—10,000 ohm pot
C_1—.001 μfd., 600 v. mica or ceramic capacitor
C_2—.01 μfd., 600 v. mica or ceramic capacitor
C_3, C_4—.1 μfd., 600 v. capacitor
C_5—50 μfd., 25 v. elec. capacitor
C_6, C_7—.075 μfd., 1000 v. capacitor
C_8, C_9—20 μfd., 450 v. elec. capacitor
C_{10}, C_{11}, C_{12}, C_{13}—80 μfd., 450 v. elec. capacitor
C_{14}, C_{15}—50 μfd., 150 v. elec. capacitor
C_{16}, C_{17}—20 μfd., 450 v. elec. capacitor
CH_1—Reactor (Chicago-Standard RC 8300)
CH_2, CH_3—Reactor (Chicago-Standard RC 1585)
T_1—Power trans. 1100-740-150 v. @ 300 ma.; 5 v. @ 6 amps; 6.3 v. @ 5 amps; 6.3 v. @ 1 amp. (Chicago-Standard PCR-300)
T_2—Output trans. (Chicago-Standard "Super Range" BO-14)
SR_1, SR_2—Selenium rectifier, 130 v. @ 20 ma.
V_1—6SN7 tube
V_2—5687 tube
V_3, V_4—6550 tube
V_5, V_6—5U4 tube
V_7—6X4 tube



Intermodulation distortion of the amplifiers, 60 and 5000 cps, mixed 4:1.

bring the amplifier distortion down to the same order of magnitude as the residual of the meter used in these tests, *i.e.*, .1% at 100 watts. Thus the total feedback of about 20 db in both sides of the push-pull stage brings the net feedback to 34 db applied to the whole amplifier.

Some attention must be paid to balance of the push-pull stages if this phenomenally low figure of distortion is to be realized. The best way is to adjust the balance control while observing either harmonic or IM distortion. A second choice is to read a.c. grid voltages on the 6550's and adjust the balance control for equal amounts on each grid. If neither of these methods is possible it will be sufficiently accurate to adjust the balance control to give equal resistances in the plate and cathode of V_{1B}.

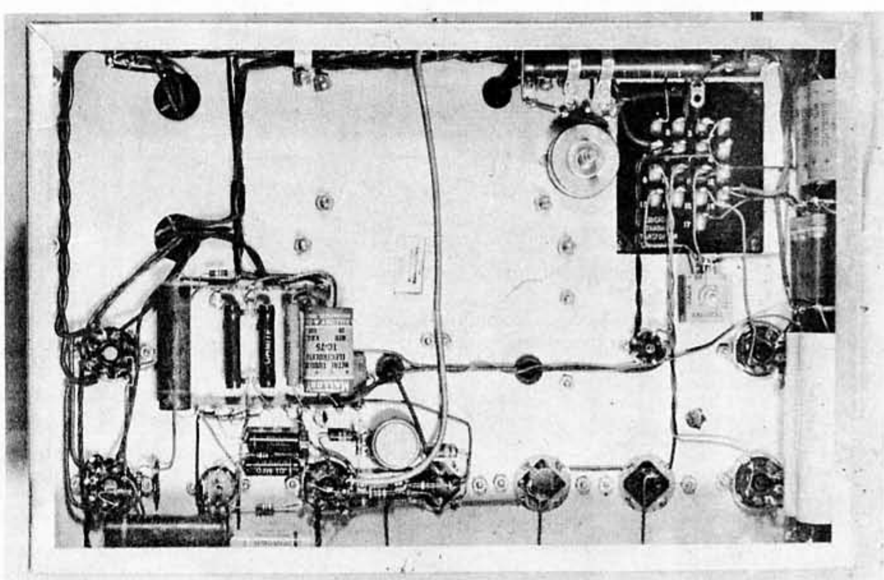
Power output developed by the tubes and supplied to the output transformer will be 100 watts. Feedback circuit losses plus transformer losses will reduce the power supplied to the load to about 90 watts. An input level of two volts is required for full output.

Triode Operation

A triode amplifier can be built using the same major components as the pentode-connected amplifier. The power and output transformers are admirably suited to the triode requirements. By using choke input on the high-voltage supply, the proper plate voltage will be obtained for triode-connected 6550's. The screen supply is now no longer needed and its components can be dispensed with. For greatest economy the bias supply can also be omitted, and self bias used. In this case the power output delivered to a load will be 25 watts. If fixed bias is used, an additional plate voltage equal to the bias voltage then becomes available, and the output will be 30 watts. In either case the same low figures of distortion will be obtained. Required input level is 1.6 volts.

Tertiary feedback can also be profitably employed. However, since the initial stage gain is lower than in the case of the pentode version, less feedback becomes available with the same tertiary winding. Nevertheless it is profitable to use this kind of feedback since it alone will reduce amplifier distortion to 0.4%. Feedback on both sides of the push-pull stage is 7 db and with 14 db of feedback added around the output transformer, residual distortion is too low to be measured. Calculated IM distortion is 0.08% and this is borne out by examination of the residual oscilloscope trace of IM meter output. These figures were obtained by merely balancing the drive voltages to the 6550 grids. If an IM meter is available it is possible to get the IM down to about 0.06% at 25 watts equivalent sine-wave output.

The extreme simplicity of the pentode amplifier is revealed by this underchassis view. The power transformer has lugs rather than leads. The PCR-300 specified has leads and is suggested herein since it is less expensive.



These remarkably low figures of distortion are due in part to the superlative output transformer. By using the transformer at one-fourth of the output power capabilities, distortion contributed by the transformer is virtually zero.

"Ultra-Linear" Operation

The output transformer used for pentode and triode operation also has taps for "Ultra-Linear" operation placed at the position on the plate winding which gives minimum distortion. The feature of "Ultra-Linear" operation is that an output power greater than that obtained from triodes can be obtained at a distortion level intermediate between that of triodes and pentodes without the complication of a screen supply.

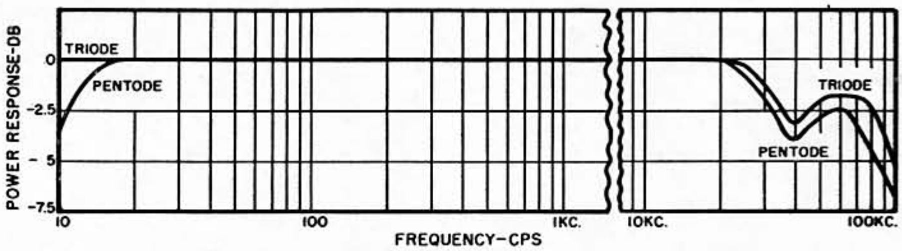
It has been experimentally determined that small amounts of tertiary feedback do not produce any reduction of distortion in this case, probably because of masking effects of the screen feedback. However, sufficient feedback is available in this output transformer to bring about a four times reduction in distortion through use of the tertiary winding alone. Addition of 14 db of outside feedback to this 12 db of tertiary feedback brings the net amplifier distortion to 0.25% IM. Amplifier input required is 1.7 volts for full output of 40 watts sine-wave power using self bias on the 6550's and essentially the same components and circuitry as for the triode version.

Feedback Considerations

No instability problems will be experienced in using tertiary feedback since it is applied around only one stage. For this reason it is well to use as much feedback as possible in this position in the circuit. Fortunately it turns out that with a given tertiary winding, greatest feedback will be obtained in a pentode stage where it is most needed. Fidelity obtained in the pentode circuit is very nearly comparable to that of a triode stage using the same transformer. In view of the greater power efficiency of pentodes, triodes will be the second choice in a circuit of this type.

Tertiary feedback has been tried with other tube types with similar good results. It seems that this kind of feedback should find wide application in low power amplifiers, where the smaller driving voltages required simplifies the design problem.

To equal the performance of most amplifiers on the market, it will not be necessary to use feedback around the output transformer in addition to tertiary feedback. But since there are no problems peculiar to combining these two kinds of feedback, it is a relatively simple matter to add outside feedback. It should be noted that outside feedback will not be necessary to reduce the amplifier output impedance since tertiary feedback will take care of that matter.[2]



Maximum power output of pentode and triode versions of the 100-watt amplifier.

The considerations involved in applying feedback around several stages seem to be well known but not always applied. In simplest terms, the requirement is that all stages except one shall have a flat frequency response extending well past both ends of the audio-frequency spectrum, and that one stage shall be rolled off in response at both ends of the spectrum. Failure to observe these principles in several near-copies of the *Williamson* circuit has sometimes resulted in unstable performance and consequent unjustified criticism of the *Williamson* circuit. The greatest error in current practice is to ignore the requirement at the high frequency end where ripest opportunities for trouble exist. Conditions of resonance or near resonance in the output transformer at ultrasonic frequencies will usually produce the amount of phase shift required for oscillation unless steps are taken to reduce amplifier gain at those frequencies. A very simple means of doing this is by a resistance-capacitance combination introduced at the plate of V_{1A} (R_1-C_1). If this is omitted, the tube and wiring capacitances must be trusted to do the job, and they may not.

At the low-frequency end of the spectrum the primary shunt inductance of the output transformer in series with the output tube plate resistance furnishes a smooth roll-off. The trouble which sometimes arises, manifested by motorboating, is due to not carrying the amplifier frequency response flat for enough below the transformer's roll-off frequency. This situation is aggravated by today's output transformers which are designed with the large inductance necessary to get low intermodulation distortion. The roll-off frequency, then, is so low it is inconvenient to use interstage coupling networks large enough for the requisite frequency response. Requirements for low frequency roll-off can be more efficiently met by tailoring one of the interstage coupling networks. Either the last stage or driver stage input coupling capacitors can be reduced in size. The phase shift introduced will be in the opposite direction of that due to transformer inductance and will tend to offset the latter in a beneficial way. Since a low value of grid resistance is specified for the 6550's, the logical place to use small coupling capacitors is at these grids.

The finished amplifier embodying these principles is stable and trouble-free. No ringing appears on square-wave response. In the pentode-connected amplifier, frequency response is down 3 db at 100 kc. from mid-frequency response, and down zero db at 20 cps. This is excluding R_2-C_2. It is wise to include R_2-C_2 to reduce possible unwanted signals below the audible spectrum. The amplifier will deliver fully as much undistorted power at 20 cps as at mid-frequencies.

It may occur to the reader that it should be possible to use the transformer secondary as the feedback winding. On output transformers that have 4, 8, and 16-ohm taps, the center tap of the 16-ohm winding is at 4 ohms. If the 4-ohm tap is grounded, the ends of the winding coil could be returned to the cathodes of the output stage. This reasoning neglects the fact that the output winding has a low impedance load imposed on it, whereas the tertiary does not. As a result, the voltage fed back is unsuitable, especially where the load is a loudspeaker with its varying resistance and reactance. No simple substitute for the tertiary exists.

A choice of a maximum of 14 db feedback around the output transformer was made for several reasons. First, that amount is usually sufficient to bring distortion below that of most amplifiers on the market. Second, if more feedback were used, amplifier input voltage requirements would be beyond that which can be obtained at low distortion from some preamps. Third, instability problems are less likely to occur. Tertiary feedback does not aggravate the stability problem in applying outside feedback, rather it eases the problem. Stable operation with as much as 40 db outside feedback has been obtained by proper attention to control of frequency response.

Current feedback can be more readily applied than in conventional amplifiers. One way of looking at the situation is to consider that tertiary feedback reduces amplifier distortion, and current feedback around the output transformer reduces loudspeaker distortion. However, in a general purpose or distribution amplifier, current feedback may be undesirable and therefore has been omitted. Those desiring it can easily include it by placing an adjustable resistor of not more than two ohms in series with the output winding and returning the cathode of V_{1A} to the junction. The negative voltage feedback from the output should then be omitted.

Two clear-cut advantages result from use of a tertiary winding: an amplifier of lower distortion can be built, and feedback is more easily applied without oscillation troubles. This has made it possible to produce an amplifier setting a new high standard combining features of fidelity, efficiency, simplicity, and power output.

REFERENCES

1. Kiebert: *"System Design Factors for Audio Amplifiers," 1954 Convention Record of the IRE.*

2. Williamson & Walker: *"Amplifiers and Superlatives," Journal of the AES, April 1954*

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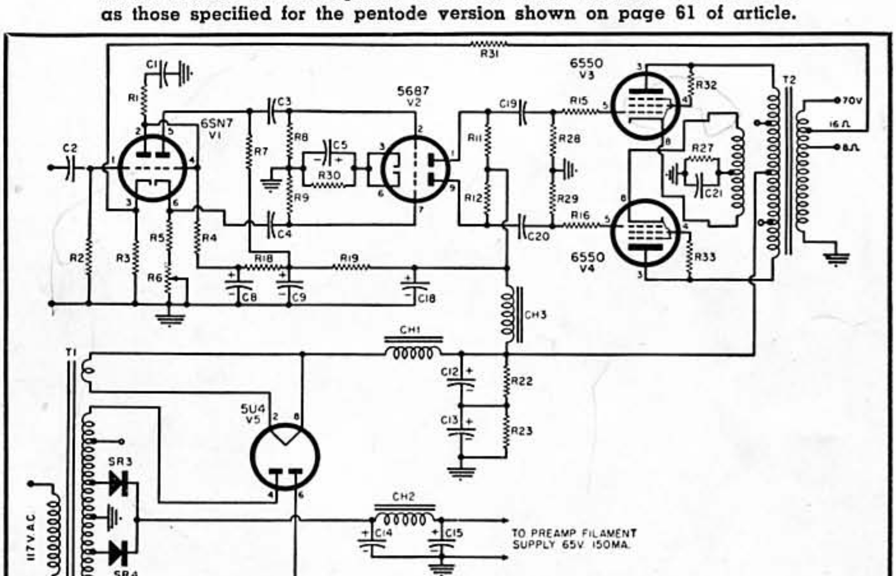
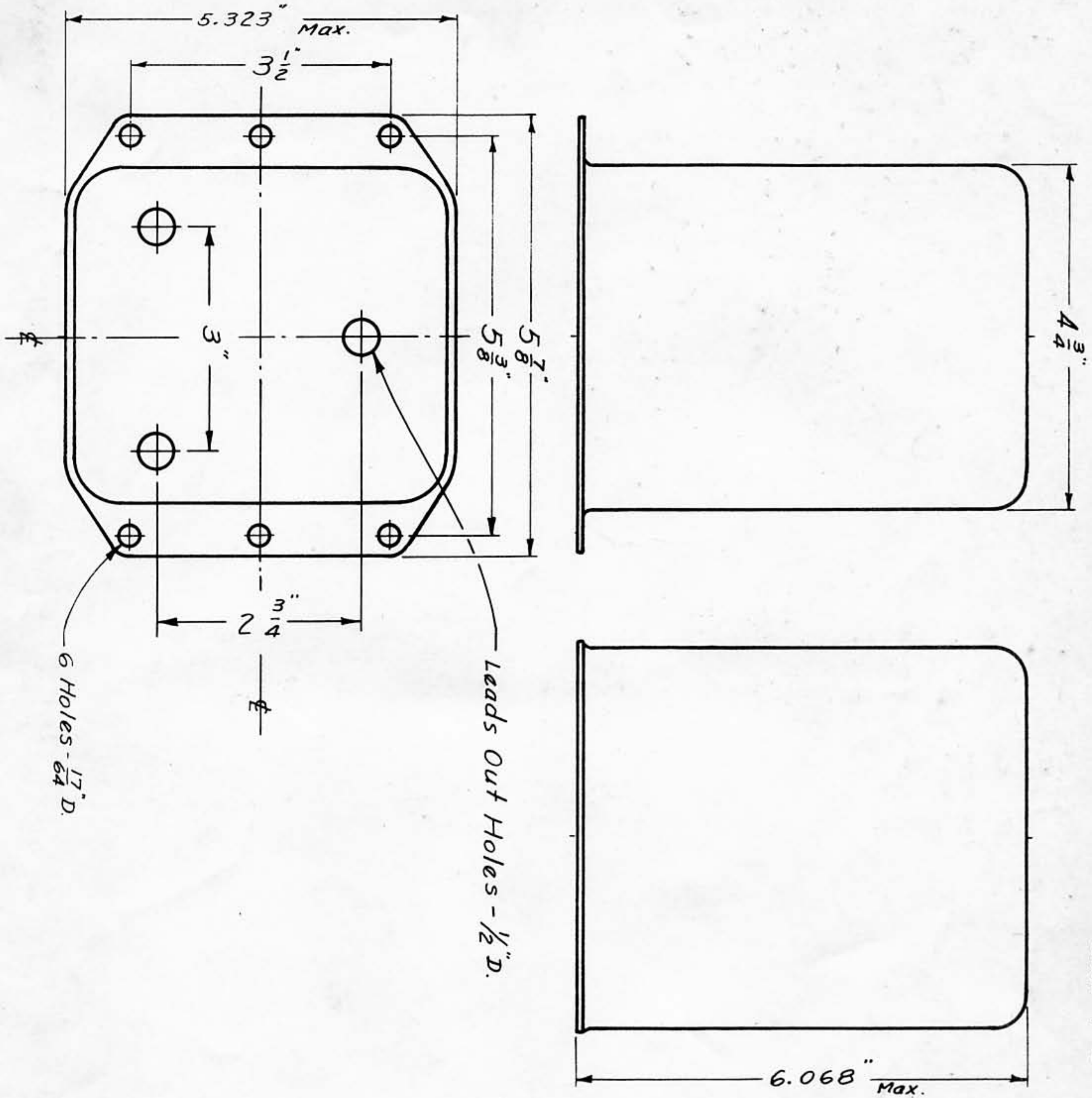
Triode version of the amplifier. Parts not listed herewith are the same as those specified for the pentode version shown on page 61 of article.



R27—300 ohm, 10 w. res.
R28, R29—220,000 ohm, ½ w. res.
R30—1200 ohm, 1 w. res.
R31—3300 ohm, 2 w. wirewound res (IRC Type BW-2)
R32, R33—220 ohm, ½ w. res.
C18, C21—20 µfd., 450 v. elec. capacitor
C19, C20—.02 µfd., 1000 v. capacitor
SR3, SR4—Selenium rectifier, 130 v. @ 75 ma.

All other parts are the same as shown in parts list accompanying pentode version (Page 61).

TOLERANCE DECIMALS ± FRACTIONS ± .031" UNLESS OTHERWISE SPECIFIED DO NOT SCALE DRAWING



SCALE — 1" = 2"

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MATERIAL

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DRAWN

CHECKED

MOUNTING DIAGRAM

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P. P. Output Trans.	
CUST. -	
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BO-14