A 3,000-Watt Audio Power Amplifier*

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Summary—**A 3,000-watt audio power amplifier has been developed using the Bereskin power amplifier circuit described at the 1954 IRE National Convention and in the March–April 1954 issue of the IRE TRANSACTIONS ON AUDIO. Solutions were found for some interesting problems that arose in this connection. A unit capable of delivering more than 3,000 watts with less than 2 per cent distortion over a 400–6,000 cycle frequency range was developed. The design procedure and test data on the final unit will be discussed.**

INTRODUCTION

A NUMBER of successful design variations of the Bereskin Power Amplifier[1] have been produced since the circuit was conceived. These have included various power and frequency ranges, in particular a 3,000 watt unit which presented a number of problems leading to what are believed to be interesting solutions. It is the purpose of this paper to discuss these problems and their solutions and to present experimental test data on the completed unit.

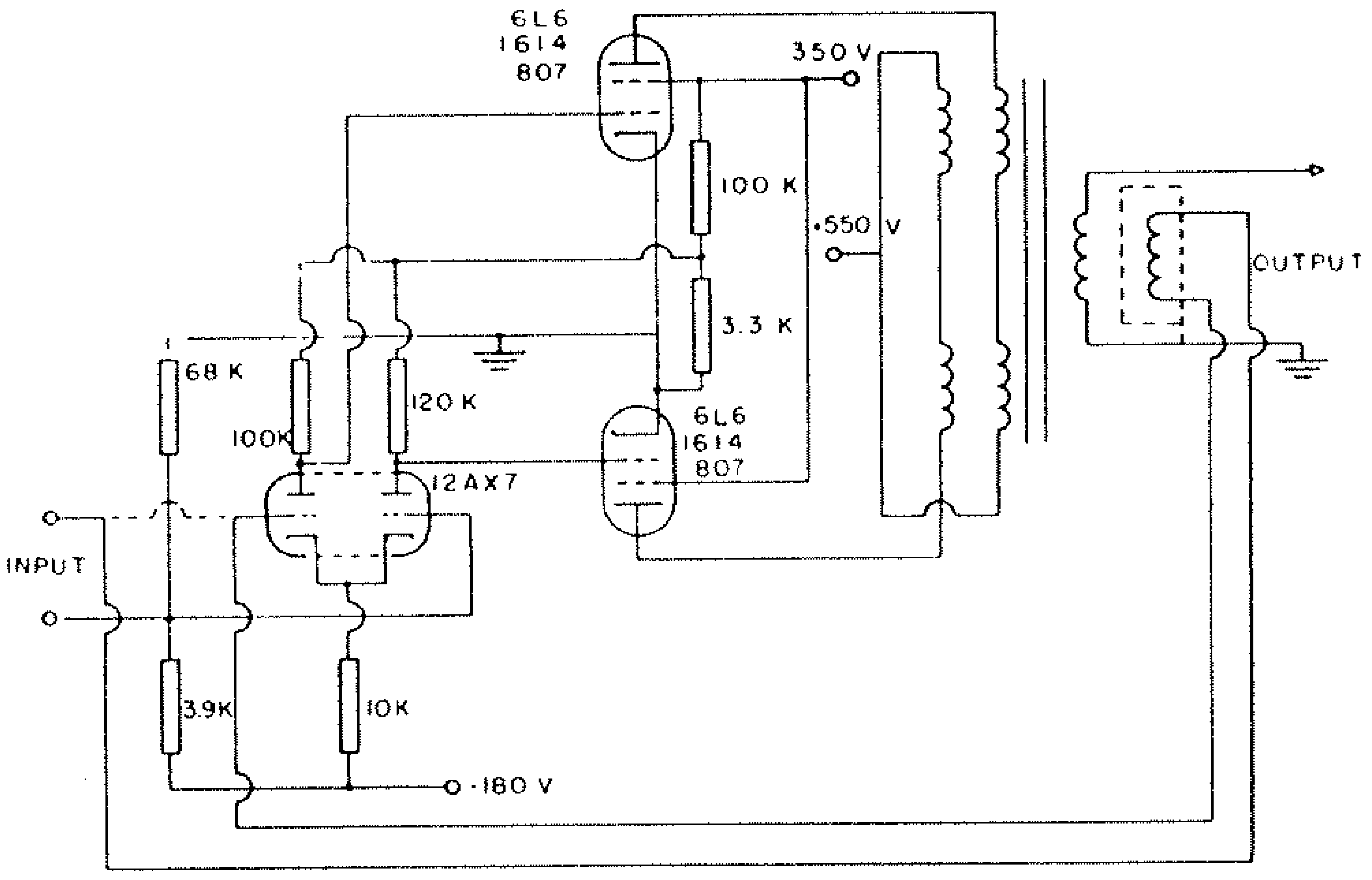

Fig. 1—Basic Bereskin power amplifier circuit.

BASIC CIRCUIT

Fig. 1 shows the basic circuit of the Bereskin Power Amplifier. In this circuit two beam power tubes are connected in push-pull with their cathodes at common ground potentials. The screens are fed from any suitable power supply which need not be derived from the plate power supply. The screen and plate supply voltage may therefore be chosen independently to best suit the particular application.

The dual triode acts as a direct coupled phase inverter and driver supplying enough bias and drive for Class B_1 operation of the beam power tubes. Class B operation of the output tubes requires that the output transformer primaries be bifilarly wound in order to avoid the conduction transfer notch. A feedback winding, closely coupled to the bifilar primary and to the secondary, and statically shielded from them, is connected in series with the input to the grid of the left-hand section of the dual triode. Good coupling between the bifilar primary and the secondary is assured by dividing the primary into two sections and sandwiching the secondary between these two sections.

This type of circuit has produced stable operation with 40 db of feedback, but this amount of feedback requires an excessive amount of driving voltage so that a value closer to 25 db is generally used. Due to the large amount of feedback used, the circuit is relatively insensitive to screen and plate supply ripple and regulation. The input signal may be either transformer- or impedance-coupled to the phase inverter-driver. Resistance-capacitance coupled input has been found to be relatively unsatisfactory due to the large dc resistance introduced in the grid circuit of the input triode. Grid current flow in this resistance tends to produce dc bias unbalance in the output tubes.

An appreciable amount of capacitance exists between the bifilar wound primaries of the output transformer. This capacitance tends to limit the high-frequency power delivering capacity of the amplifier. This undesirable effect of the primary interwinding capacitance is reduced by operation at low plate signal voltage and high plate signal current. The capacitance itself can be reduced by approximately one third by transposing the bifilar winding at each turn.

DESIGN PROBLEMS AND SOLUTIONS

The specifications for the power amplifier proper required that it be capable of delivering 3,000 watts in the frequency range between 400 and 4,000 cycles per second with a distortion not to exceed 10 per cent. The amplifier developed was able to deliver the required power with less than 2 per cent distortion.

Investigation and analysis of available tubes showed that a pair of 4-1000A tubes operated Class B_1 push-pull would be capable of delivering slightly in excess of 3,000 watts within the rated plate and screen dissipation if operated with 5 kv plate supply voltage and 1.25 kv screen voltage.

Information of this type is not usually available in the tube data supplied by the manufacturer. In order to develop the permissible peak plate currents without

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[1] A. B. Bereskin, "A high-efficiency, high-quality audio-frequency power amplifier," TRANS. IRE, vol. Au-2, pp. 49–60; March, 1954; IRE CONVENTION RECORD, Part 6, Audio and ultrasonics, pp. 18–24.
A. B. Bereskin, "Fifty-watt amplifier for high-quality audio," *Electronics*, vol. 27, pp. 160–164; October, 1954.

TABLE I

POWER DELIVERING CAPACITY CALCULATIONS
($E_{bb}=5$ kv, $E_{c2}=1.25$ kv)

$E_{c2}=1$ kv $e_{c1}=0$ v		$E_{c2}=1.25$ kv $e_{c1}=0$ v		
e_b (volts)	i_b (amp)	e_b (volts)	i_b (amp)	W_{max} (watts)
600	.930	750	1.252	2,660
800	1.130	1,000	1.520	3,040
1,000	1.270	1,250	1.710	3,210
1,200	1.340	1,500	1.805	3,160

positive grid voltage drive it is necessary to operate the tubes with screen voltages considerably in excess of the values specified for Class AB_2 and B_2 operation. This is generally permissible if the various insulation and power dissipation limitations are not exceeded.

Insulation limitations must be determined either from manufacturer's data or by test. For this particular tube EIMAC specifies in pamphlet Number 3, "Pulse Service Notes," that the 4-1000A tube may be operated with 2.5 kv screen voltage and 15–30 kv plate supply voltage in pulsed operation. While the operation involved here is not of the pulsed variety, the insulation available is believed to be entirely adequate for the purpose.

The determination of plate and screen dissipation requires transposition of the available plate and screen characteristics to values corresponding to the desired value of screen voltage. This can be done if it is remembered that the voltage field pattern and the current distribution will not be altered if all interelectrode voltages are either raised or lowered by the same relative amount. The current values, however, will take on new values in accordance with the 3/2 power law.[2] (EIMAC suggests that the use of the 4/3 power provides more accurate information.) If an adequate amount of feedback is used then it can be assumed that a sinusoidal input signal will result in sinusoidal plate current and plate voltage variation.

The manner in which the deliverable power can be computed is shown in Table I above. Here the first two columns were obtained from the $e_{c1}=0$ v, $e_{c2}=1$ kv data supplied by the manufacturer. Columns 3 and 4 represent computed data for $e_{c1}=0$ v, and $e_{c2}=1.25$ kv. Column 3 was obtained by multiplying the values in column 1 by 1.25. Column 4 was obtained by multiplying the values in column 2 by $1.25^{4/3}=1.347$. Column 5 represents the maximum ac power that can be developed in Class B_1 push-pull operation for $e_{c2}=1.25$ kv when $e_{b\min}$ and $i_{b\max}$ correspond to the values in columns 3 and 4 respectively and a plate supply voltage of 5 kv is used.

Maximum average plate dissipation, with sine wave signal, will occur when the plate is driven 2/3 of the way to zero volts, corresponding to a peak ac signal voltage of 3,333 volts. For the condition of row 2 in Table I this results in a peak plate current of 1.27 amperes and an average plate current, for the two tubes, of .805 amperes. The dc input power is therefore 4,025 watts while the ac plate power developed is 2,115 watts. The maximum average plate dissipation is therefore 1,910 watts. The condition of row 1 would not supply the required 3,000 watts of output power while the conditions of rows 3 and 4 would have plate dissipation conditions exceeding the rated value of the tubes.

Maximum screen dissipation occurs at maximum drive. Table II, opposite, shows manner in which information can be set up to compute the expected screen dissipation and other important quantities assuming sufficient feedback is used to force a cosine variation of plate current and plate voltage.

The value of zero signal tube plate current was arbitrarily chosen at .100 ampere to produce 50 per cent of rated plate dissipation. This represents a reasonable compromise between severity of Class B bias and quiescent plate dissipation.

Fourier analysis applied to the data of Table II yields the following information:

$I_b=.980$ ampere
$I_{c2}=.118$ ampere
Screen dissipation = 148 watts
Plate circuit input power = 4,900 watts
AC power developed = 3,040 watts
Plate dissipation = 1,860 watts
Plate efficiency = 62 per cent

This last tabulation indicates that the operating conditions chosen will yield the required power output within the plate and screen dissipation ratings of the tubes chosen. Of course the correct operating conditions are rarely obtained on the first choice and a few incorrect operating conditions may have to be investigated before the correct one is determined.

There is no dc voltage between the two primaries, but an instantaneous peak voltage of 4,000 volts appears between adjacent points of these windings at full signal. Commercially available polyvinyl chloride, Teflon, and Kel-F insulated wires have been found to have adequate insulation strength for this purpose. Polyvinyl chloride insulated wire is not satisfactory because of its high dielectric constant (6.5), which would produce a high primary interwinding capacitance and thereby interfere with the high-frequency power delivering capacity, and its high power factor (0.10) which would produce excessive insulation temperature rise. Both Teflon and Kel-F had acceptable dielectric constant and power factor. Kel-F insulation had the advantage of higher dielectric strength, listed as high as 2,500 volts per mil, high resistance to cold flow, and lower cost. At the time of this development polystyrene foam insulation was being discussed in the literature but was not commercially available. This insulation would have a marked advantage from the point of view of dielectric constant which would approach 1.00.

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[2] EIMAC Tube Reference Data on 4–65A tube, p. 6.

TABLE II

MAXIMUM SIGNAL PERFORMANCE CALCULATIONS

($E_{bb}=5$ kv, $E_{c2}=1.25$ kv, $e_{b\min}=1$ kv, $i_{b\max}=1.52$ amp)

	At operating value of E_{c2} (1.25 kv)			At nearest available curve value of E_{c2} (1.0 kv)				At operating value of E_{c2} (1.25 kv)	
θ (degrees)	e_b (volts)	Composite i_b (amp)	Tube i_b (amp)	e_b (volts)	Tube i_b (amp)	e_{c1} (volts)	i_{c2} (amp)	e_{c1} (volts)	i_{c2} (amp)
0°	1,000	1.520	1.520	800	1.130	0	.350	0	.471
22.5°	1,310	1.405	1.405	1,050	1.043	−17	.120	−21.2	.161
45.0°	2,180	1.072	1.072	1,745	.798	−44	.040	−55.0	.054
67.5°	3,470	.581	.581	2,780	.432	−78	.015	−97.5	.020
90.0°	5,000	0	.100	4,000	.074	−140	0	−175	0

Its other characteristics would require further investigation.

The wire used for the bifilar primaries was #22 (7-30) wire with .014-inch wall of Kel-F insulation. Twisted samples of this wire were tested with 20 kv peak 60 cycle power without breaking down. The manufacturer specifies that 100 per cent of wire of this type with .008-inch wall is subjected to an Insulation Flaw ("Spark") Test with an impressed voltage of 7,500 volts rms. Samples of the .008-inch wall wire must also pass the manufacturer's test of a four-hour immersion in tap water, with the wire ends left out of the water, with a subsequent application of 5,000 volts rms for one minute between the conductor and the tap water. All of these tests represent appreciably greater dielectric stress than that encountered between the two adjacent wires of the bifilar winding. No trouble has been experienced due to the lack of insulation in the bifilar winding.

Preliminary calculations indicated that the high-frequency power delivering capacity would begin to fall off at frequencies slightly below 4 kc, so it was decided to take advantage of the reduction in primary interwinding capacitance obtained by transposing the bifilar winding at every turn. Subsequent performance tests showed that the high-frequency power delivering capacity specifications would have just barely been met without this refinement but were quite adequately met with the refinement.

The output transformer was designed to be used with two Moloney MA-306 grain oriented C cores. The winding buildup for this transformer is shown in Fig. 2

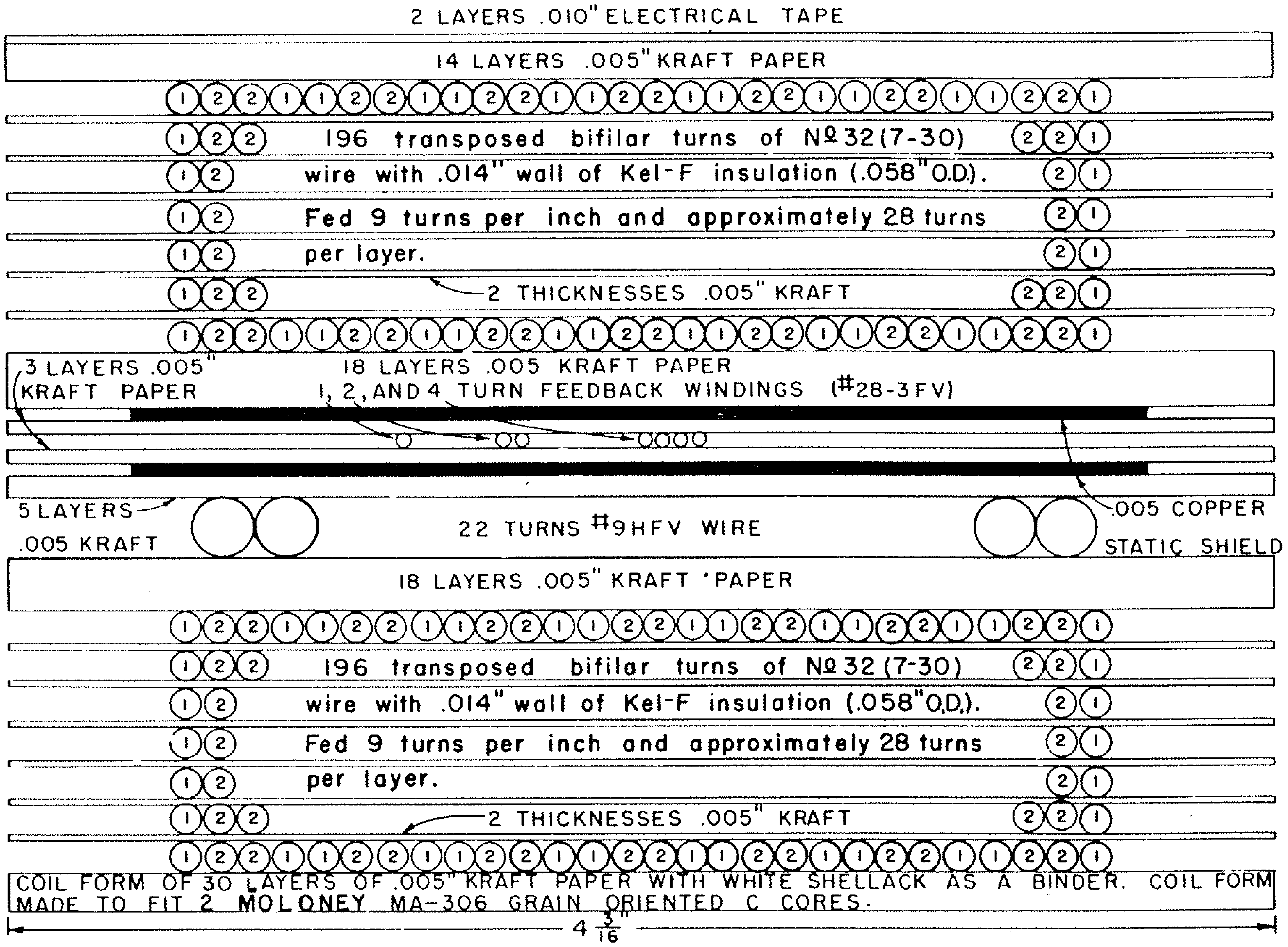

Fig. 2—Output transformer coil buildup for 3,000-watt power amplifier (proper proportions on vertical scale only).

and the complete circuit diagram is shown in Fig. 3.

In order to supply the grid driving voltage required by the 4-1000A tubes without introducing excessive grid circuit resistance, the double triode was replaced with two 6AU6 tubes. This provided the additional convenience of being able to provide dc balance by adjustment of the 6AU6 screen voltages. The choke in the impedance coupled input is a Thordarson T20C51 choke modified by full interleaving of the laminations. The voltage limits of the plate and screen supply voltages are also shown in Fig. 3.

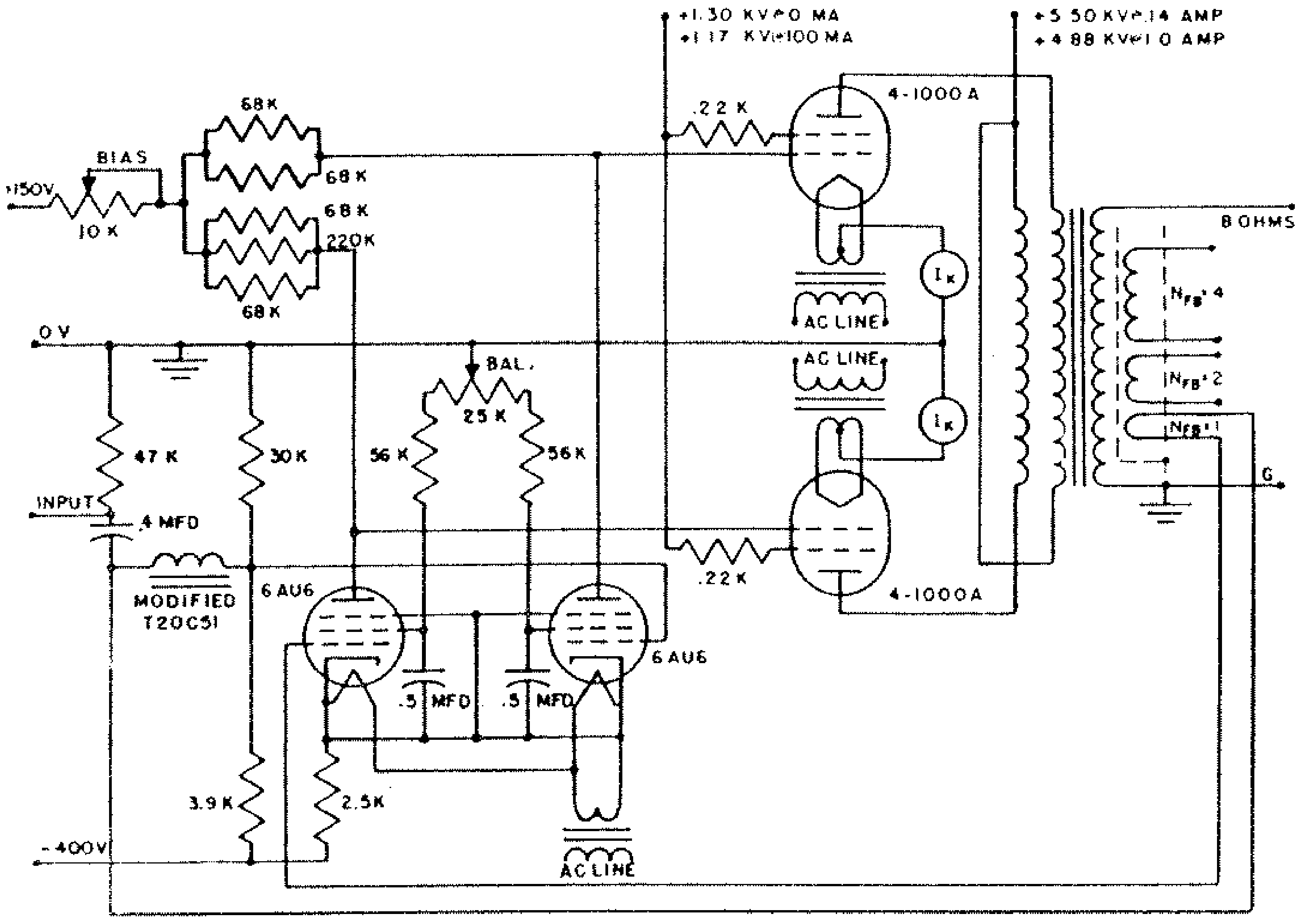

Fig. 3—3,000-watt audio power amplifier.

PERFORMANCE

The effect of various amounts of feedback on the residual hum and on the full signal input voltage required is shown by the curves in Fig. 4. Operation of this amplifier was stable with the maximum possible feedback of 30 db corresponding to the full seven turns in series. A single feedback turn corresponding to 13 db provided an adequate hum level 57 db below 3,000 watts and only required 8.7 volts input voltage for 3,000 watts output. The remaining tests were performed using the single turn feedback winding.

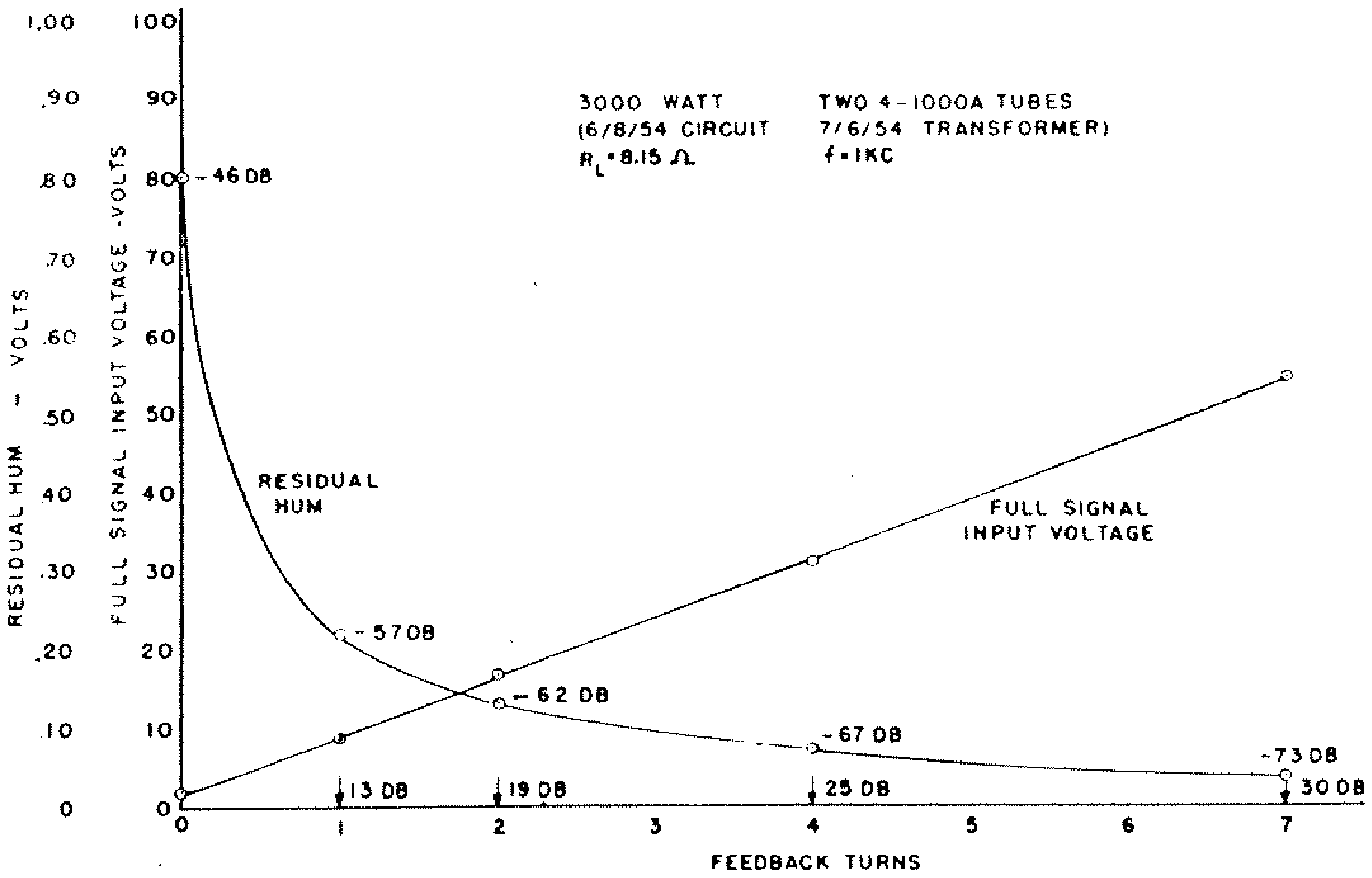

Fig. 4—Feedback analysis characteristics.

The 1 kc power loss and distortion characteristics are shown in Fig. 5. The plate dissipation curve in this figure was obtained by subtracting the transformer losses from the total plate circuit losses. The plate dissipation exceeds the rated value by 2 per cent in the 1.4 kw output region while the screen dissipation remains below the rated value up to full power output.

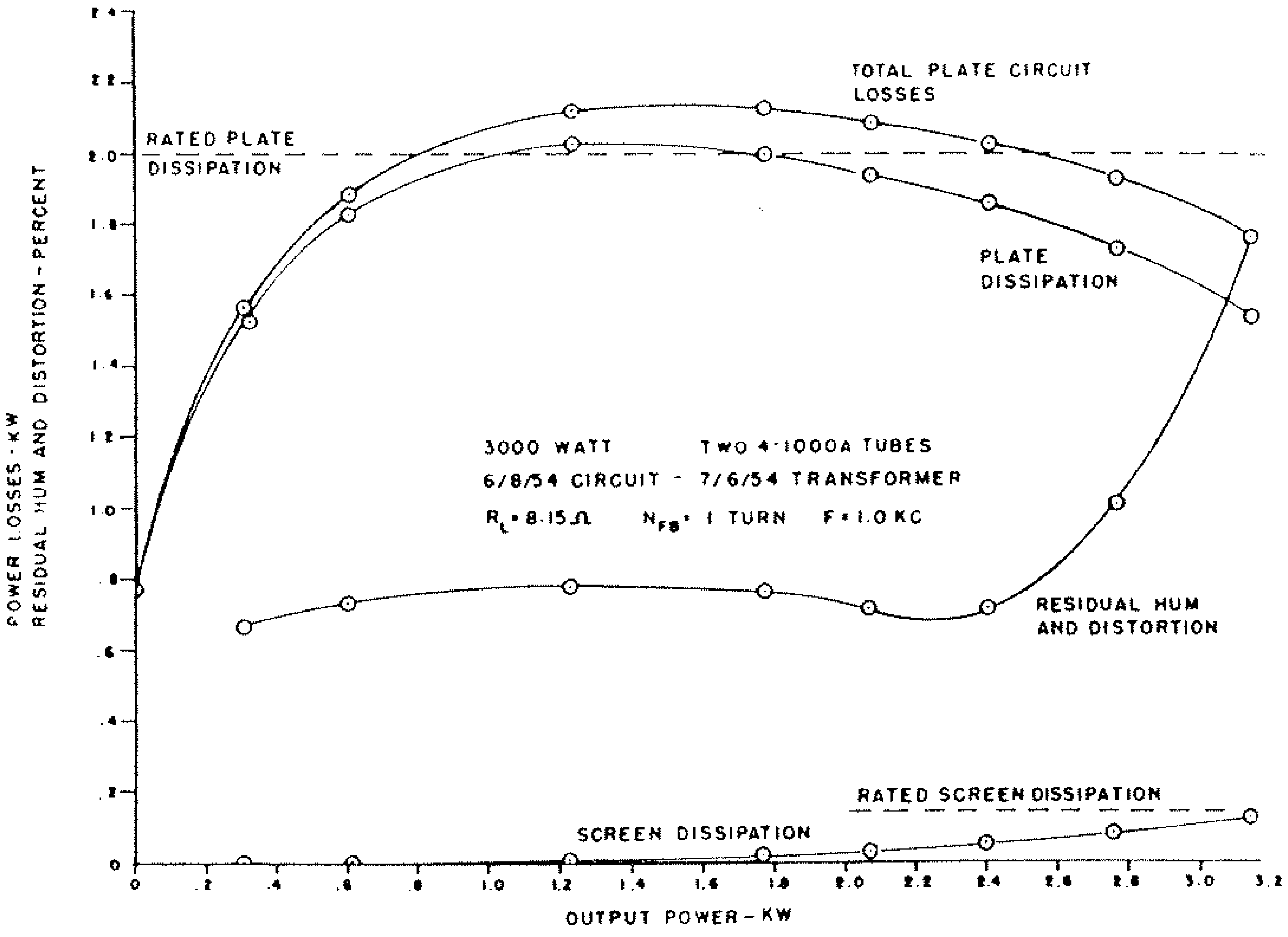

Fig. 5—Power loss and distortion characteristics.

Residual hum and distortion remains at about 0.8 per cent over most of the operating region, rising rapidly to 1.4 per cent at 3,000 watts output. Additional reduction in the residual hum and distortion could have been obtained by using more feedback but the performance was already much better than that required by the specifications.

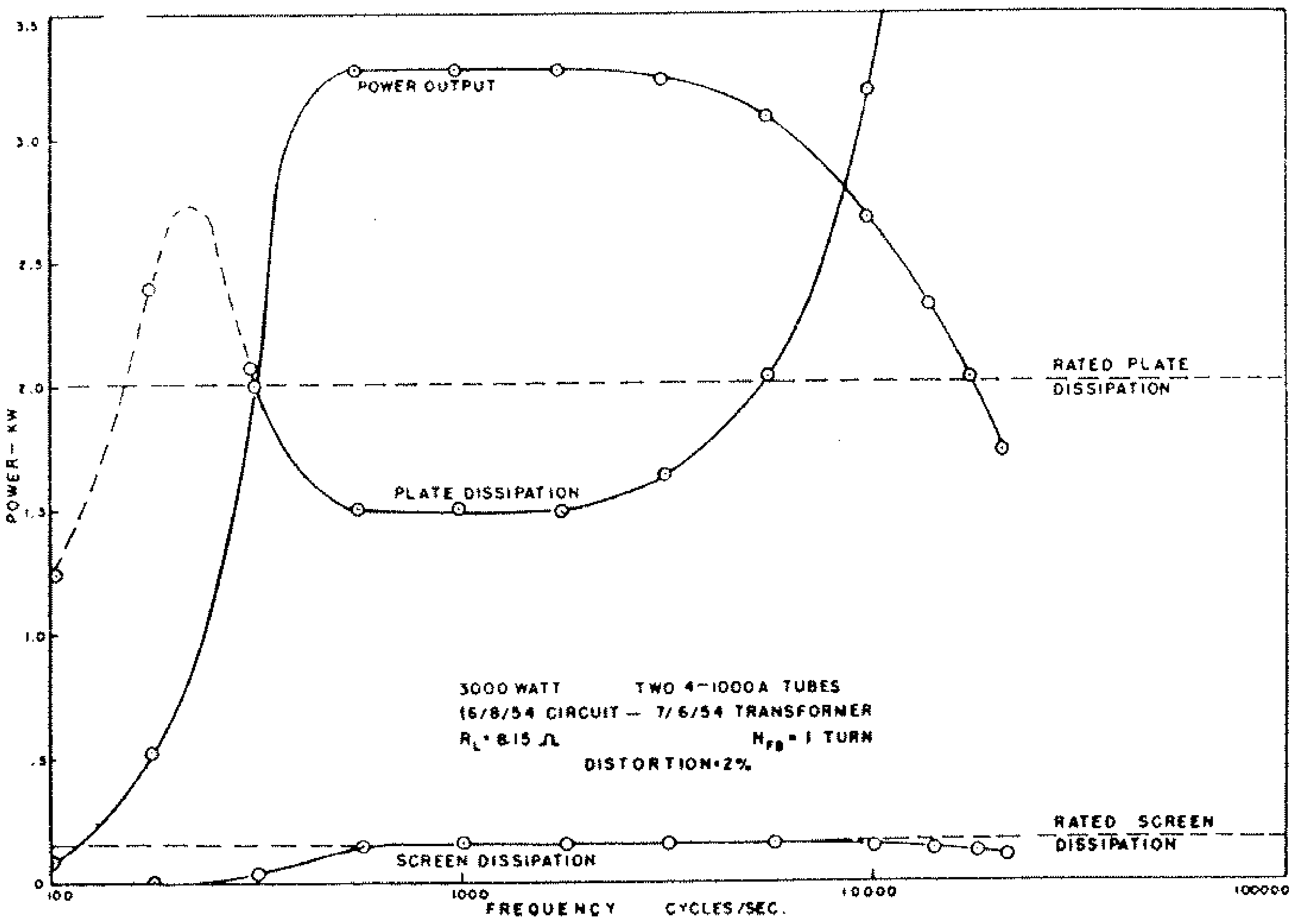

Fig. 6—Two per cent distortion power relations.

The power delivering capacity of the amplifier is shown in Fig. 6. At each of the frequencies shown in this figure the input was adjusted to produce 2 per cent distortion in the output. The amplifier is capable of delivering in excess of 3,000 watts within the plate and screen dissipation ratings of the tube over the required frequency range of 400 to 4,000 cycles per second.

The frequency response characteristics are shown in Fig. 7. The upper curve in this figure is the 2 per cent distortion power delivering capacity plotted to a db scale. The lower curve is the low level frequency response characteristic obtained by maintaining constant input voltage while varying the frequency. This characteristic deviates by less than 1 db from the middle frequency response over a frequency range of 100 to 38,000 cycles per second. The low frequency peak in response is due to series resonance between the input capacitor and the modified T20C51 choke.

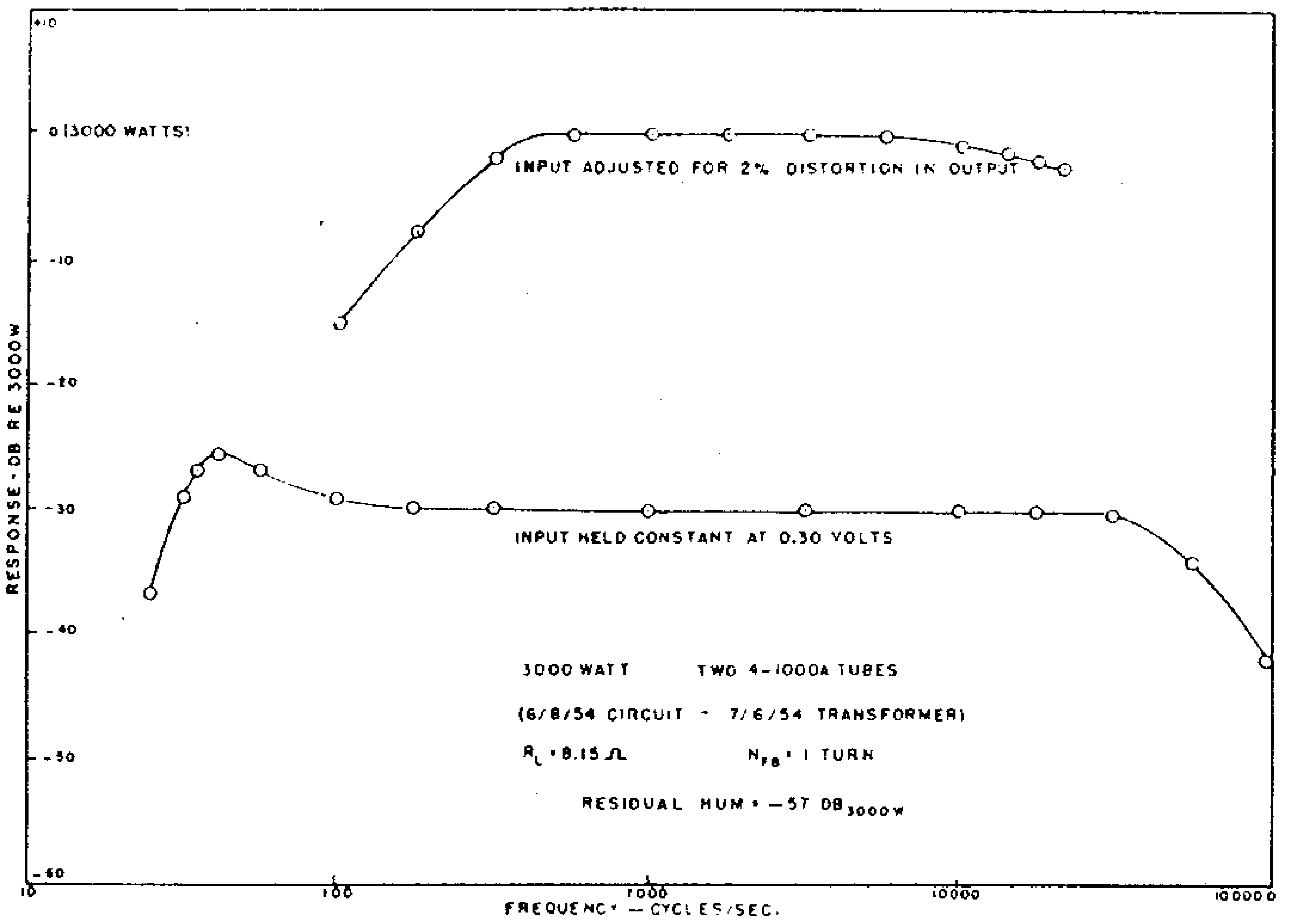

Fig. 7—Frequency response characteristics.

Fig. 8 is a photograph of the completed amplifier, exclusive of power supplies showing the chassis arrangement of the various components and the blower used for forced draft cooling of the tubes and transformer. The bottom of the chassis was enclosed and the blower provided positive air pressure inside the chassis. The air was allowed to escape through the air system sockets for cooling the 4-1000A tubes and through suitably located holes for cooling the transformer.

A characteristic of this type of amplifier is that the transition from very low power level to very high power level is made in a single step. The relative size of the two 6AU6 tubes used to drive the two 4-1000A tubes is clearly seen in Fig. 8.

The transformer, complete with mounting hardware, weighs 26.5 pounds, while the complete amplifier shown in Fig. 8 weighs 54.5 pounds.

Only one unit of the amplifier under discussion was required. If another unit had been required certain minor modifications would have been introduced in the transformer construction. The primary and secondary turns would be increased by approximately 40 per cent and the primary wire size would be changed to #24 (7-32) with a .014-inch wall of Kel-F insulation. The secondary wire size would have been changed to #10 Heavy Formvar. The changes indicated should reduce the 1 kc-2 per cent distortion core loss from 204 watts to 114 watts while increasing the copper loss from 20 watts to 40 watts. The increase in copper loss is not serious and the decrease in core loss is highly desirable. The increase in turns should move the low-frequency end of the power delivering capacity curve to the left so that this curve would cross the 3,000 watt level at about 280 cycles per second. The increase in number of turns would tend to increase the primary interwinding capacitance but this would be overcome to a large extent by the reduction in the wire size so that the high-frequency power delivering capacity would not be expected to change appreciably.

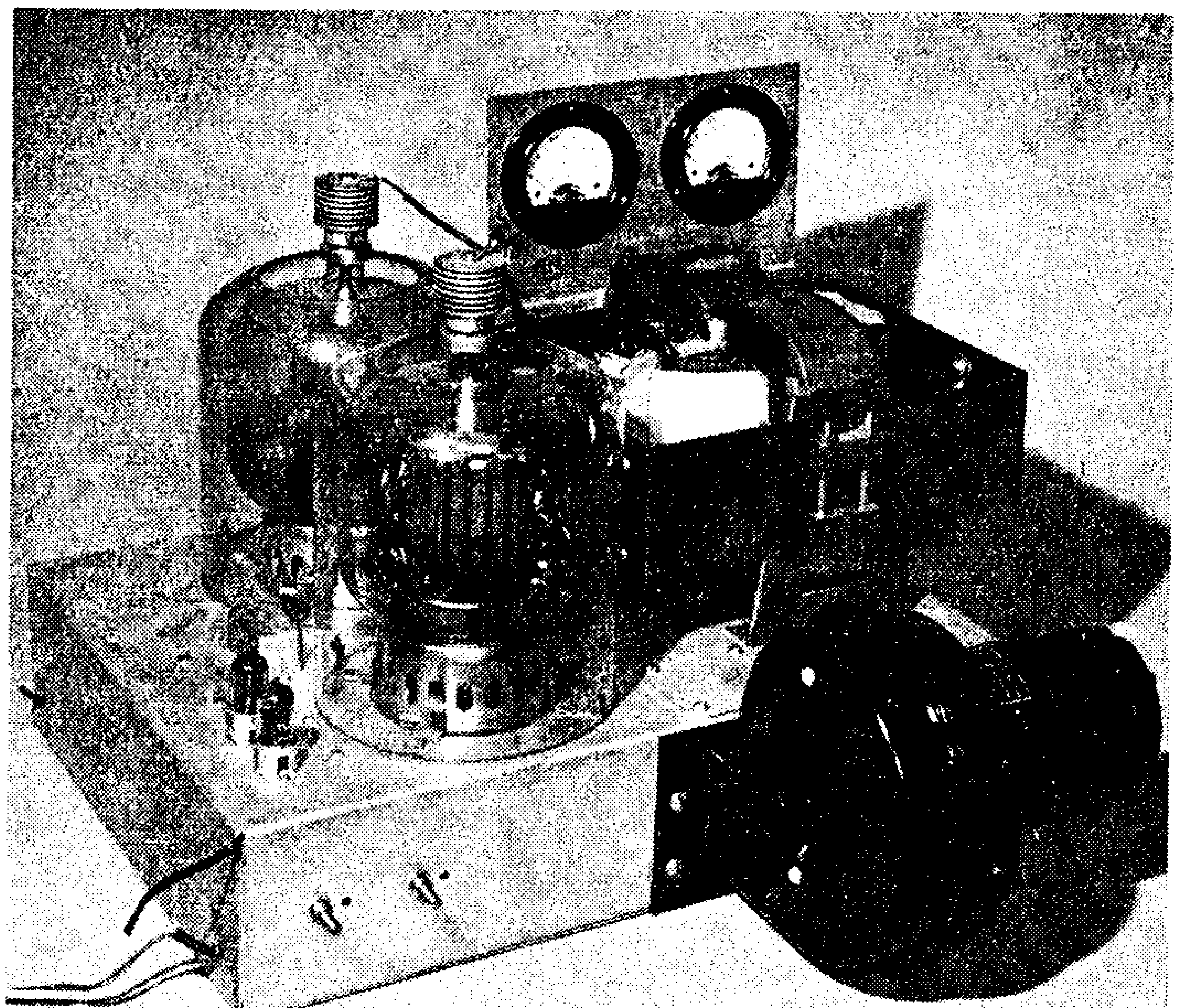

Fig. 8—3,000-watt audio power amplifier.

If the specifications had called for operation at considerably lower frequencies than those required, the transformer would have been designed with a much larger magnetic path cross section. Modifications in the number of turns and wire size would also have to be made.

The amplifier developed satisfied all of the design specifications and showed very good correlation between design data and final performance.

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