LB-1012

A 20-WATT TRANSISTOR AUDIO AMPLIFIER

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Approved

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This bulletin describes a 20-watt audio amplifier using six p-n-p germanium junction transistors. Three are experimental power transistors of the type described in *LB-1010*[1]; the others are RCA type 2N-109 transistors. The class B output stage is connected in a single-ended push-pull circuit driving a conventional 16-ohm loudspeaker directly, without using an output transformer. The amplifier is a-c operated. It has high input impedance, suitable for crystal pickup or microphone. The operation is satisfactory for ambient temperatures from -5 degrees centigrade up to 55 degrees centigrade (approximately 25°F to 130°F).

A discussion of the power capabilities of transistors and some aspects of power-transistor class-B operation precedes the description of the amplifier.

Power Capabilities of Transistors

The maximum power that can be dissipated in a transistor before "run away" occurs depends on a number of factors of which the most important is the ability to remove heat. This ability when heat is removed by conduction is measured by the thermal resistance, i.e., the internal temperature rise per unit power of dissipation. The lower the thermal resistance, the greater the power handling capability. Factors which determine the maximum power dissipation capability are collector voltage, the current amplification factor, and the reverse saturation current. An approximate expression for the maximum permissible dissipation of a germanium transistor connected in a circuit having substantially no external emitter and collector circuit resistances (such as the one to be described) is

$$P_{max} = \frac{23}{\theta} \log_{10} \left(\frac{10}{\theta V \alpha_{CB} I_S}\right) \text{ watts} \qquad (1)$$

where θ = thermal resistance in °C per watt
V = collector voltage in volts
α_{CB} = a-c collector-to-base current amplification factor
I_S = base saturation current in amperes at chassis temperature.

Note that the I_S used in this formula should correspond to the temperature of the chassis on which the transistor is mounted. P_{max} decreases at approximately the rate of $1/\theta$ watts per degree centigrade increase in chassis temperature.

Application of Eq. (1) to an experimental power transistor of the type used in this amplifier serves as a pertinent example. For this unit, θ = 5°C/w, α_{CB} = 15, I_S = 0.45 ma at 60 degrees C (assumed highest chassis temperature). If the collector voltage is 25 v, from Eq. (1) P_{max} = 5 watts per transistor.

Some Aspects of Power-Transistor Class-B Operation

The class B operation of junction transistors has been discussed in some detail in *LB-975, Class B Operation of AF Junction Transistors*. It was pointed out that the theoretical efficiency of 78 per cent for a sine-wave output can be approached with transistor class-B amplifiers. However, for fixed power-supply voltage, the maximum dissipation occurs when the amplifier is delivering a square-wave

[1] *LB-1010, Recent Advances in Power Transistors.*

output approximately equal to four-tenths of maximum sine-wave output power.[2] Thus the ratio of maximum sine-wave push-pull output to the maximum possible dissipation in each transistor is 4-to-1. If the limit of dissipation is 5 watts per transistor, the maximum output power is 20 watts. For ordinary speech or music signals, the average dissipation per transistor is far below one-quarter of the maximum output power.

To operate two transistors in a push-pull class B amplifier either "double-ended" (Fig. 1a) or a "single-ended" (Fig. 1b) connection[3,4] may be used. The single-ended connection, which requires no output transformer, eliminates both distortion and loss which would arise from the use of a transformer. Transformerless output operation also eliminates possible ill effects of transformer leakage inductance. This kind of connection is particularly suitable for power transistors working directly into a conventional loudspeaker load.

For a single-ended push-pull class B stage, the required d-c supply voltage, V, and current, I, for a maximum sine-wave output, P, into a load resistance, R can be derived as follows: assuming an undistorted sine-wave

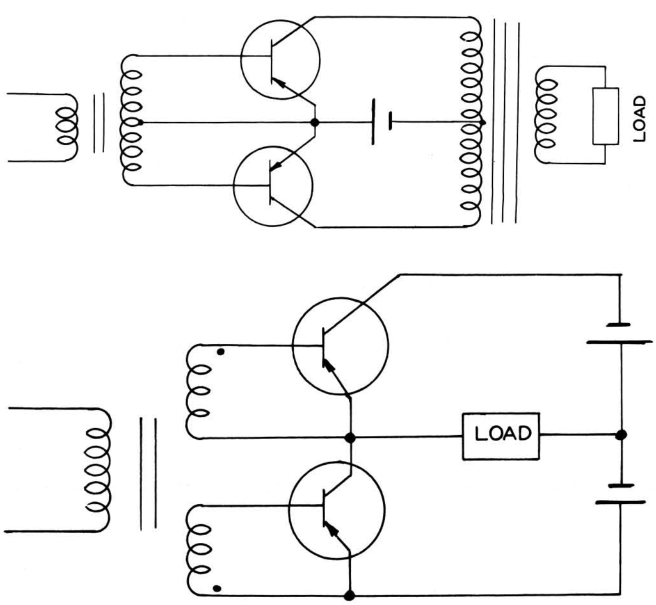


Fig. 1 - Push-pull transistor amplifier.

[2] L. J. Giacoletto, "Power Transistors for Audio Output Circuits", *Electronics*, Jan. 1954.

[3] *LB-935, A Transformerless Audio Amplifier for Use with Conventional Loudspeaker.*

[4] A. Peterson and D. B. Sinclair, "A Single-Ended Push-Pull Audio Amplifier", *Proc. IRE*, Jan. 1952.

output voltage which swings from zero to twice the d-c collector voltage per transistor, the load resistance should equal the ratio of V to I_m, the peak current. Since I_m equals π times the d-c collector current,

$$R = V/\pi I \qquad (2)$$

The maximum sine-wave output is equal to $\pi/4$ times the d-c input power to the two output transistors, hence

$$P = (\pi/4) \cdot 2 \cdot VI \qquad (3)$$

Combining Eqs. (2) and (3) gives

$$V = \sqrt{2PR} \qquad (4)$$

$$I = (1/\pi)\sqrt{2P/R} \qquad (5)$$

A single-ended circuit connected as shown in Fig. 1b would not operate satisfactorily at room temperature because of the absence of "threshold" bias between the base and emitter. Without the bias, the transistors operate class C instead of class B, i.e., each transistor conducts *less* than half the time. Such operation would give rise to "cross-over" distortion which would be particularly severe at low output levels. The required forward biasing voltage decreases with increase in temperature at a rate of approximately 2½ millivolts per degree centigrade for germanium transistors.[5] A suitable biasing network should therefore include a temperature-sensitive element, for example, a thermistor. The temperature-sensitive element should be thermally coupled as tightly as possible to the transistor which is to be compensated, in order that the temperature-sensitive element respond to the temperature of the transistor.

Circuit Description

A complete schematic diagram of the 20-watt audio amplifier is shown in Fig. 2. Transistors V_1 through V_3 are RCA Type 2N109 p-n-p transistors. They form a preamplifier which permits operation from a capacitive source, such as a crystal microphone or crystal phono-

[5] *LB-977, Temperature Effects in Circuits Using Junction Transistors.*

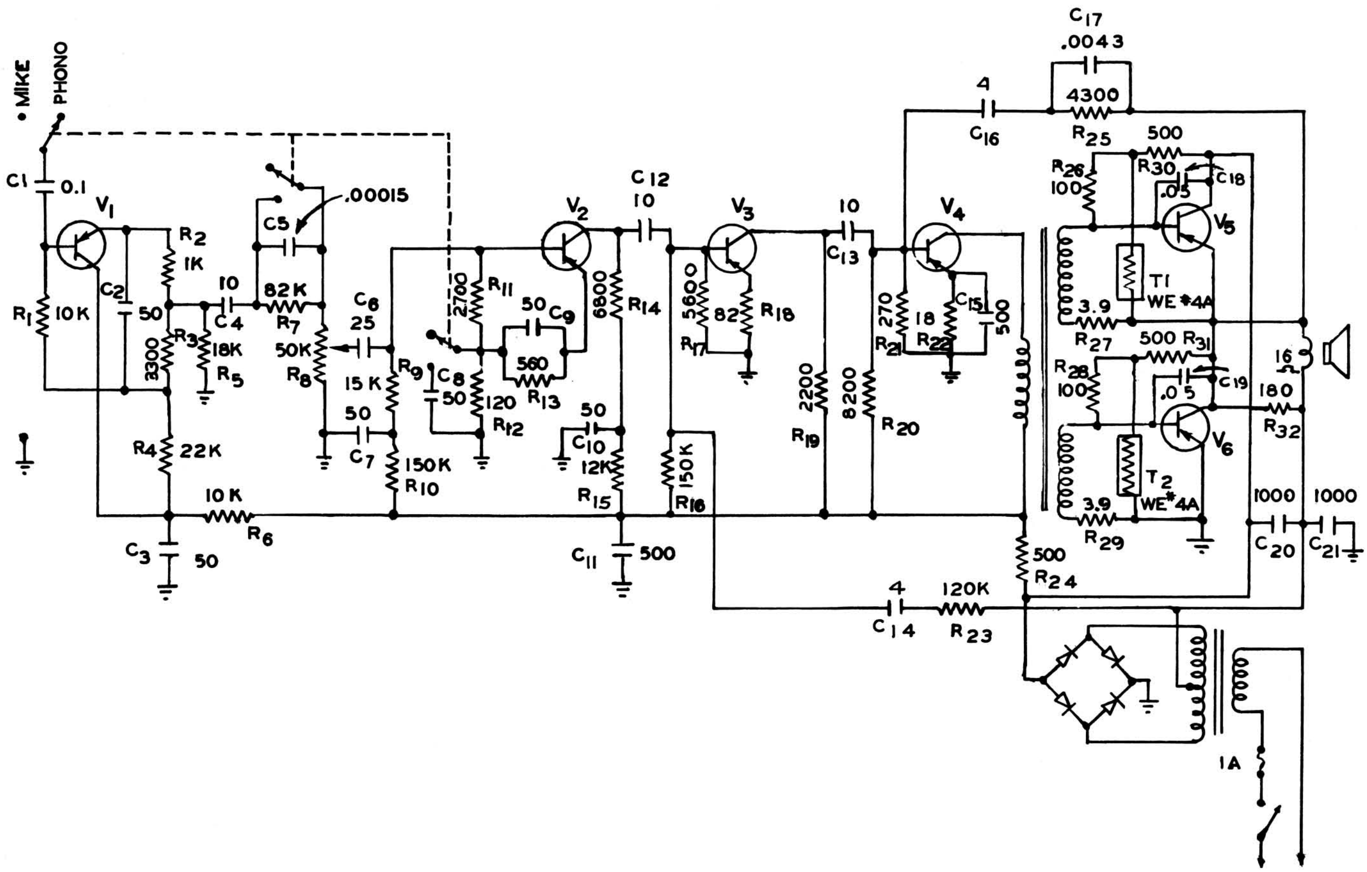


Fig. 2 - Schematic diagram.

graph pickup. Transistors V_4 through V_6 are the experimental power units previously mentioned. Transistor V_4 operates in a class A driver stage, while V_5 and V_6 are employed in the class B transformerless output stage.

(a) Preamplifier

The input stage is a modified version of a grounded collector amplifier, and has a high input impedance. The resistor, R_2, in series with the emitter, stabilizes the d-c operating current against temperature variations. Resistors R_3, R_4, and R_5, form a voltage divider for deriving proper potential for each electrode. The base resistor, R_1 is returned to a point at emitter potential (a-c) instead of ground potential. This permits a smaller value of base return resistance to be used without causing input circuit loading. A small value of base resistance improves the operating current stability.

The second and third stages are in grounded emitter configurations. External emitter resistances are used to stabilize the transistors against temperature variations and provide interchangeability of transistors. The base-to-emitter biases are derived from voltage dividers. The external base return resistance of every stage is made less than the product of the current amplification factor and the emitter resistance to achieve good temperature stability.[5] Emitter resistances, with the exception of R_{18}, are adequately bypassed to avoid signal degeneration. Resistor R_{18} is not bypassed because of hum considerations, as will be explained later.

The volume control follows the first stage. Both input and output of the volume control are coupled through capacitors in order to avoid flow of direct current, which would make the control noisy. A parallel RC network is incorporated in the input to the volume control to compensate for the high frequency fall-off in current amplification of the transistors. The value of C_5 may be changed somewhat to compensate for variations in frequency response due to the pickup and the recording. This compensating network is short-circuited in the microphone position to provide a needed increase in gain.

The volume-control setting affects the input impedance of the amplifier; the lower the setting, the higher the reflected input impedance. When a capacitive input device such as crystal pickup is used, a higher impedance input gives greater low-frequency response. Thus the volume control can be designed to give the desired tone compensation.

(b) Driver

The driver stage uses a power transistor operating class A in the grounded-emitter connection. The resistor, R_{22}, in series with the emitter, stabilizes the d-c operating current as temperature is varied. It is bypassed by capacitor, C_{15}, at audio frequencies. The base-to-emitter bias is derived from a voltage divider R_{20} and R_{21}.

The output of the driver is transformer-coupled to the output stage.

Since the metal enclosure of the power transformer is electrically connected with the collector, it must be insulated from the main chassis which is at ground potential. At the same time, the metal enclosure should be in good thermal contact with the main chassis in order to remove the heat generated in the transistor. For these purposes, an anodized aluminum plate, which insulates electrically but conducts thermally, is sandwiched between the power transistor and the main chassis.

(c) Output Stage

The output stage is connected in "single-ended push-pull" transformerless output configuration. As explained previously, the optimum base-to-emitter bias for class B operation decreases by approximately 2.5 millivolts with every degree centigrade of temperature rise. This bias is derived from a series-parallel combination of thermistors (T_1, T_2) and resistors (R_{26} to R_{31}).

As in the driver stage, the output transistors are mounted on anodized aluminum plates to provide low thermal resistance between the transistors and the main chassis. The thermistors are also mounted on these anodized plates to insure tight thermal coupling between the transistors and the thermistors.

The input is transformer-coupled to provide the required out-of-phase input voltage for the two transistors. The secondary windings are tightly coupled together to avoid transient voltages when current shifts from one output transistor to the other. This is accomplished by bifilar winding. Because of the low input impedance of the power transistors (in the order of 30 ohms during conduction), the secondary is stepped down from the primary by a ratio of 5-to-1, thus providing a current gain. Transformer data are shown in Table I.

Negative feedback is employed to reduce distortion. The distortion is mainly caused by fall-off in current amplification factor at high current levels. In this amplifier negative feedback is applied over two stages. This provides a greater amount of negative feedback than can be obtained within a single stage. Negative feedback also reduces the output impedance of the output stage, thereby providing greater damping for the loudspeaker.

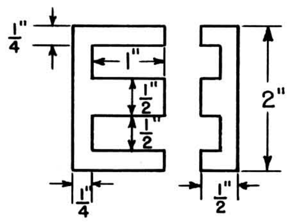
The collector-to-base current amplification factor of the experimental power transistors falls off at higher audio frequencies. There is a certain amount of phase-shift associated with this fall-off in the amplification factor, as in a low-pass filter. This phase-shift, together with that in the driving transformer, limits the maximum amount of negative feedback that can be applied in the system without causing instability. To improve the stability, the frequency response of the final stage is extended by means of local negative feedback. This is accomplished by connecting a capacitor between the collector and the base of each output transistor (C_{18} and C_{19}). Also, a step-frequency response is introduced in the high-frequency end of the feedback loop. The step reduces the phase shift, thereby stabilizing the amplifier. The frequency step is obtained by connecting a capacitor, C_{17}, in parallel with the feedback resistor, R_{25}. The total amount of feedback is 11 db at an output of 20 watts and a frequency of 400 cps. The stability margin is 9 db. The feedback is somewhat greater at lower levels because of higher current gains.

(d) Power Supply and Filtering

The power supply consists of selenium

Table I

TRANSFORMER DATA

	Driver Transformer	Power Transformer Stancor P-6308 (Modified)
Core	 ½" stack, Magnetic Metal Co. 50EE496 lamination, .002"air-gap	Core unchanged
Windings	Secondaries (bifilar) 180 turns for each winding, No. 25HF, 46 turns/layer, 8 layers, .002" paper between layers. Primary 1000 turns, No. 30HF, 80 turns/layer, 15 layers, .001"paper between layers.	Primary unchanged Secondary 448 turns, center-tapped, No. 23HF, 90 turns/layer, 5 layers, .002" paper between layers.

rectifiers connected in a bridge circuit. Two sections of 350-ma selenium rectifiers are used in each arm of the bridge. This arrangement provides a center-tap for the rectified d-c output voltage. The center-tap assures equality of the voltages applied to the output transistors regardless of unbalance in characteristics of the transistors or difference in values of the filtering capacitors, C_{20} and C_{21}. Power transformer data are shown in Table I.

The operating collector voltages and currents of the transistors for maximum sine-wave output, are listed in Table II.

Transistor collector current is normally insensitive to collector voltage variations at collector voltages greater than a few tenths of a volt; the major cause of hum is ripple current introduced at the base of the transistor. In a resistance-coupled amplifier, ripple may be fed to the base through the base-biasing resistance, and the resistance in series with the collector of the previous stage.

The necessary amount of filtering increases progressively toward the input end of the amplifier. As in vacuum-tube amplifiers, the filtering system can be *graded*.

Another source of hum occurs in the feedback path. The ripple voltage appearing at the center-tap of the power supply causes a ripple current to flow through the loudspeaker and the feedback network to the base of the driver. To

Table II

DC Operating Voltages and Currents

	V_1	V_2	V_3	V_4	V_5 & V_6
V_C in v	6	10	7	27	26
I_C in ma	1	1	9	35	560

"buck-out" this source of hum, a ripple current in opposite phase is fed to the base of the preceding transistor through R_{23} and C_{14}. The required values of R_{23} and C_{14} depend upon the current amplification factor of transistor V_3. To allow for interchangeability of transistors, degeneration is applied by means of an unbypassed emitter resistance, R_{18}. When the current amplification factor is high, the input impedance is also high. More input current is bypassed to the base return resistance, R_{17}, so that the amplified output current is substantially the same as that when using a transistor with low amplification factor.

Filtering for the output stage is furnished by the capacitors, C_{20} and C_{21}. The filtering is required to reduce the hum modulation of the signal at full voltage swings. These capacitors also serve to provide a low-impedance return path for output currents. The voltage supplied to all earlier stages is filtered through R_{24} and C_{11}. Additional filtering to the first three stages is provided by R_{16} and C_{10}, R_{10} and C_7, R_6 and C_3.

Operational Details

In operating the amplifier, care must be taken that the output terminals are not short-circuited. If the output terminals are short-circuited, a large input signal may cause excessive transistor dissipation in the output transistors.

It is also important that the output terminals are not open circuited. Open output may cause destructively-high voltage to exist across one output transistor due to unbalance in transistor characteristics, particularly if there is signal.

The output transistors should have as nearly equal current amplification factors as possible, in order that unbalanced direct current flowing in the voice coil be kept to a minimum. The permissible unbalanced current depends on the loudspeaker used and the maximum distortion which can be tolerated.

The output transistors as well as the driver transistor should satisfy the following additional requirements:

Collector breakdown voltage: > 60 volts.

Peak base current for 1 ampere peak collector current (up to 10 kc): <65 ma and >25 ma.

Peak base-to-emitter voltage for 1 ampere peak collector current:[6] <0.6 volt.

Thermal resistance: <5°C/watt.

I_{CO} at V_C of -1 volt at 25°C: <30 μa.

Performance

The overall frequency response is shown in Fig. 3. The input voltage between the base of the input transistor and ground was kept constant during the test. For phonograph input, the frequency response is within 1½ db from 40

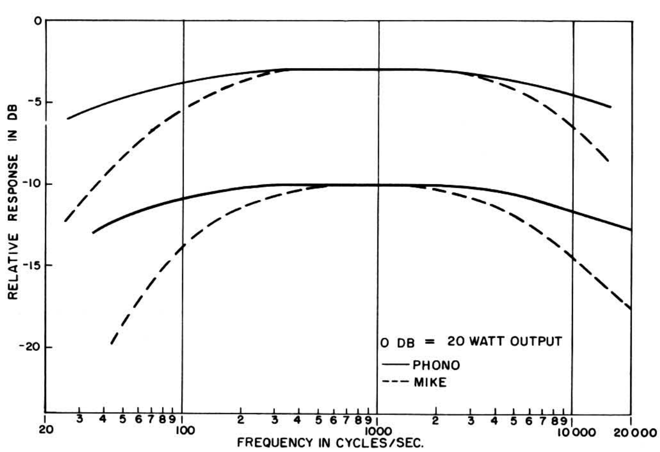


Fig. 3 - Frequency response.

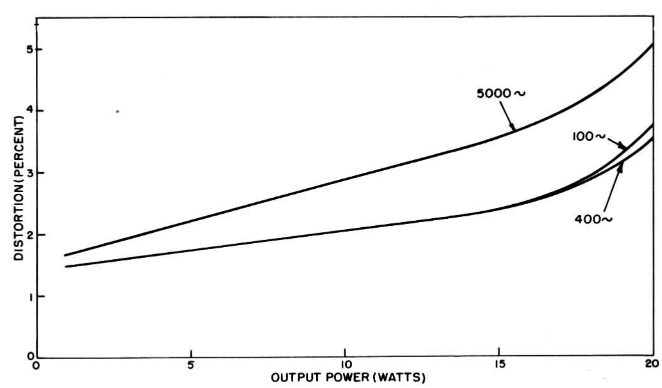


Fig. 4 - Distortion vs power output.

[6] For output pair only.

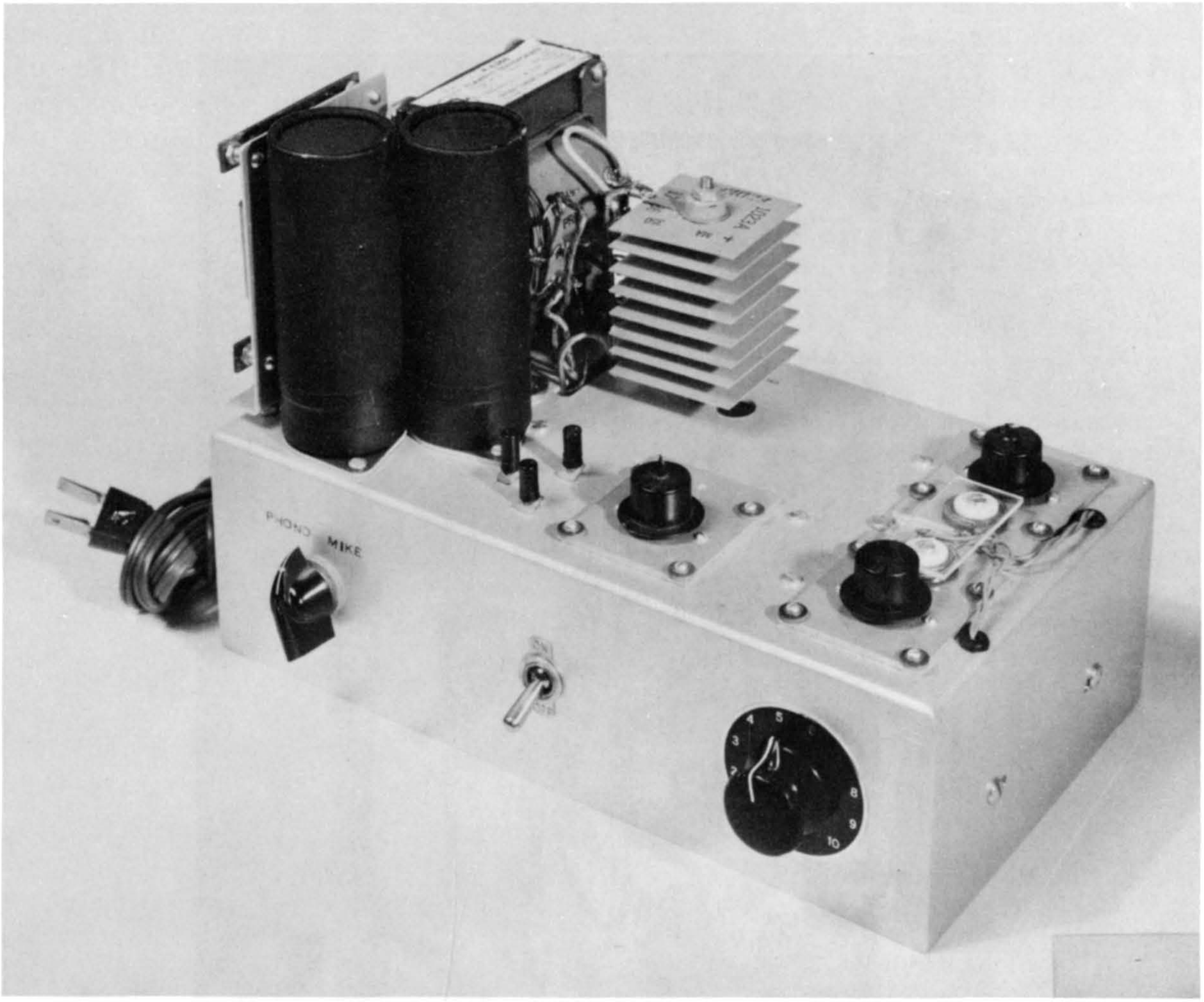


Fig. 5 - Amplifier chassis.

Table III

AMPLIFIER PERFORMANCE

Input Impedance:	1 megohm (phono) ¼ megohm (mike)
Output Impedance:	1½ ohm
Power Gain:	77 db (phono) 104 db (mike)
Harmonic Distortion:	<5% at 20 watts <3% at 10 watts
Frequency Range:	±1.5 db from 40-15,000 cps (phono)
Hum Level:	57 db below 20 watts (phono) 54 db below 20 watts (mike)
Maximum Ambient Temperature:	55°C

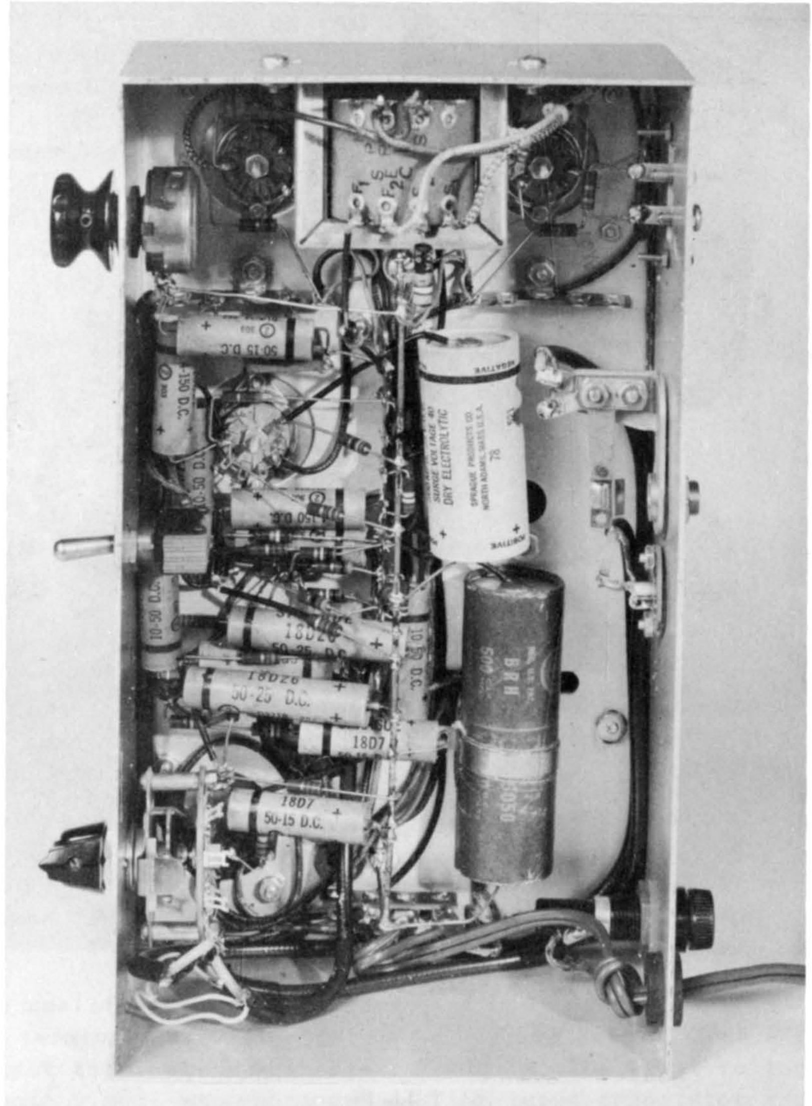


Fig. 6 - Bottom view of chassis.

to 15,000 cps. The high-frequency response for microphone input falls off because no compensation is used, as explained previously. The low-frequency response was purposely cut down to keep the hum within reasonable level (54 db below full output at maximum volume control setting). A larger bypassing capacitor than the value specified for C_8 can be used to raise the low-frequency response.

Fig. 4 shows the distortion at different output levels. The distortion at 20 watts is less than 5 per cent, and at 10 watts, less than 3 per cent. The net distortion at 5000 cycles is somewhat higher than that at lower frequencies for corresponding power levels, because of reduction in gain around the feedback loop.

The amplifier has been tested at ambient temperatures ranging from -5 degrees C up to +55 degrees C with no appreciable deterioration in performance.

Table III summarizes the performance of this amplifier.[7]

Fig. 5 shows the actual construction of the amplifier. Note the anodized plates and the thermistors. Fig. 6 shows the bottom view.

[7] Measurements were made according to RMA Standard SE - 101A.

H. C. Lin