LB-1082

# HIGH-POWER TRANSISTOR AUDIO AMPLIFIERS



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**Approved**

Stuart Wm Seeley

## Note

The transistors described in this bulletin were selected for various parameters. Since the project was a feasibility study to develop design techniques, in some cases the transistors were used above their established maximum ratings. It is not recommended that the transistors be employed in a commercial application above these ratings. The maximum emitter current for the 2N301 and 2N301A is 2 amperes. The maximum collector voltage for the 2N270 is 25 volts and the maximum dissipation is 150 mw at 50 degrees C ambient temperature.

Several models of high-power audio amplifiers have been developed and constructed which operate satisfactorily and are capable of delivering outputs of 45 watts at an ambient temperature of 50 degrees Centigrade. Series, quasi-complementary and complementary-symmetry circuits have been investigated for this application. The series circuit uses all like-conductivity transistors, requires no driver or output transformers, and uses a split-load phase inverter. The two driver transistors and the two output transistors each are in series for the d-c supply voltage and operate class B for the a-c signal. The quasi-complementary circuit employs a complementary transistor pair in the driver stage and a series type output stage consisting of like-conductivity transistors. Both the driver and output stages operate class B. Although no high-power complementary symmetry amplifier was constructed, it appears that this type circuit would be best suited for power amplifier design.

In addition to the intrinsic limitations (such as voltage breakdown and beta falloff at high currents) of present type transistors, the design of stable high-power amplifiers is also greatly dependent upon thermal considerations, all of which set an upper limit on the power-handling capabilities of the device.

The two basic conditions for stable, reliable operation of a power transistor are: (1) the maximum rated junction temperature should not be exceeded and (2) a criterion for circuit thermal stability should be met. A graphical representation of these two conditions is presented, based on experimental results, which enables the designer to determine the maximum safe operating temperature for an amplifier with a given power output. The effects of stabilization, compensation, and type of heat sink used may be determined from this presentation.

## Introduction

The use of transistors in electronic equipment usually leads to a saving in supply power, size and weight. In any particular application, one or more of these benefits will be obtained where transistors are used in a circuit design. In addition, equipment reliability can often be improved by the use of semiconductor devices.

Transistor audio amplifiers have been developed which possess the above advantages and which are capable of delivering up to 20 watts of power.[1] Most transistor circuit development, however, has been limited to low-power applications and low transistor dissipations (in milliwatts). With the advent of high-power audio transistors, it has become desirable to investigate the use of these devices in high-power audio amplifiers (in the range of 50 watts) where the transistors are operated at higher power dissipations and correspondingly high junction temperatures. Because little information is now available regarding the operation of transistors under the above conditions, it has been the purpose of this study to determine the important considerations involved in developing high-power amplifiers. In conjunction with this study, a prime objective was to design several high-power amplifiers capable of stable operation over as wide a temperature range as practical, in order to demonstrate the principles of circuit design and to illustrate the advantages gained by the use of transistors.

[1] *LB-1012, A 20-Watt Transistor Audio Amplifier.*

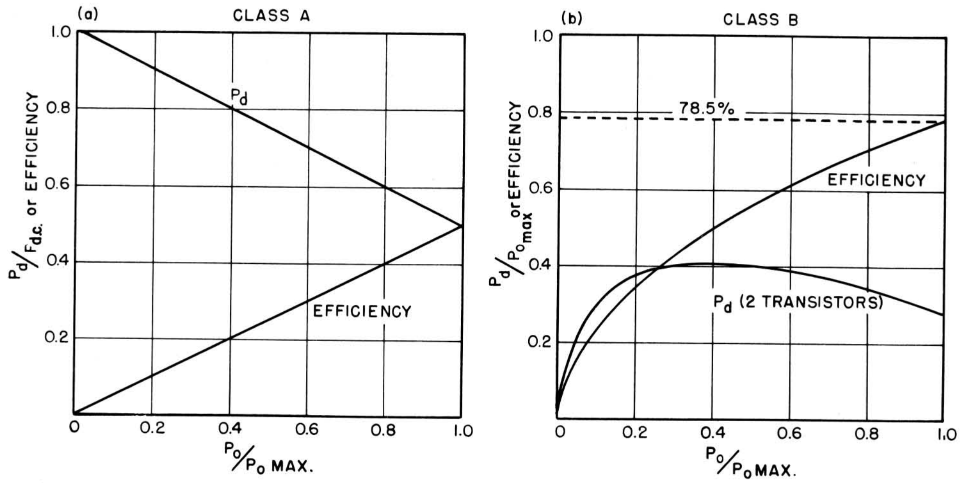



Fig. 1 - Collector efficiency and dissipation versus power output (sine wave).

Where high power output is desired, class-B operation is more desirable than class A since it offers the important advantages of low standby idling current and a higher ratio of power output to collector dissipation (high collector circuit efficiency) per transistor than can be realized in class-A operation.[2]

Fig. 1 shows the comparison of collector efficiency and dissipation versus power output for both class-A and class-B amplifiers. In an ideal class-A amplifier, maximum collector dissipation occurs at no power output (zero-efficiency) and results in large standby currents. Maximum efficiency of 50 percent is obtained at maximum power output. (Maximum power output is defined as $V^2_{cc}/2R_L$, where $V_{cc}$ is the collector supply voltage for one transistor and $R_L$ is the load resistance for that transistor.)

For ideal class-B amplifiers, the collector efficiency is zero at no power output and approaches 78.5 percent at maximum power output. Circuits with efficiencies approaching this maximum can be designed, since junction transistors have output characteristics which have sharp 'knees' at low voltages and therefore allow a voltage swing over practically the entire output characteristic. For a sine-wave signal, maximum dissipation occurs at about 40 percent of the maximum power output and is equal to 40 percent of the maximum output, as illustrated in Fig. 1(b). It is important to note that maximum dissipation does not occur at maximum power output, but at 40 percent of the maximum output. Therefore, when designing high-power amplifiers where transistor dissipation is important, this factor should be considered.

Actually, the highest dissipation occurs in class-B amplifiers with a square-wave signal whose amplitude is one-half the peak output voltage. Under this condition, the total dissipation in the two transistors is 50 percent of the maximum sine-wave power output, the dissipation of each transistor being 25 percent of the maximum output.

To take maximum advantage of the properties of transistors and their associated circuitry, it is highly desirable to design high-power amplifiers for which the size and weight of the associated components remain a minimum. In this regard, the elimination of transformers throughout the power amplifier is desirable. It is inconsistent to employ large, heavy transformers in a transistor amplifier where size and weight are important considerations. In addition, the elimination of transformer coupling improves the overall frequency response and also allows the use of more negative feedback, since the phase shift of the transformer is not added to the overall feedback loop.

Three basic circuit configurations, capable of high-power operation, have been investigated. All of them employ class-B operation of the output and driver stages and require no transformers. These three are: the series circuit, quasi-complementary symmetry circuit, and complementary-symmetry circuits. Power amplifiers using the series and quasi circuit have been constructed which are capable of delivering over 45 watts of power. No high-power complementary-symmetry circuits have been constructed, since suitable high-power n-p-n units are not available. However, from the information obtained in the design of the series and quasi circuits, and from design data for low-power complementary-symmetry amplifiers, it is possible to project these results and to formulate the performance of this type amplifier when operating at high-power output.

These amplifiers are discussed and compared in the next section of this bulletin. The appendix briefly discusses some of the considerations involved in designing high-power amplifiers from the standpoint of the

[2] *LB-975 Class B Operation of Audio Frequency Junction Transistors.*

transistor device. Temperature compensation and stabilization of power amplifiers, and some of the thermal considerations involved in high-power amplifier design, including thermal stability, are also discussed.

## High-Power Amplifier Circuits

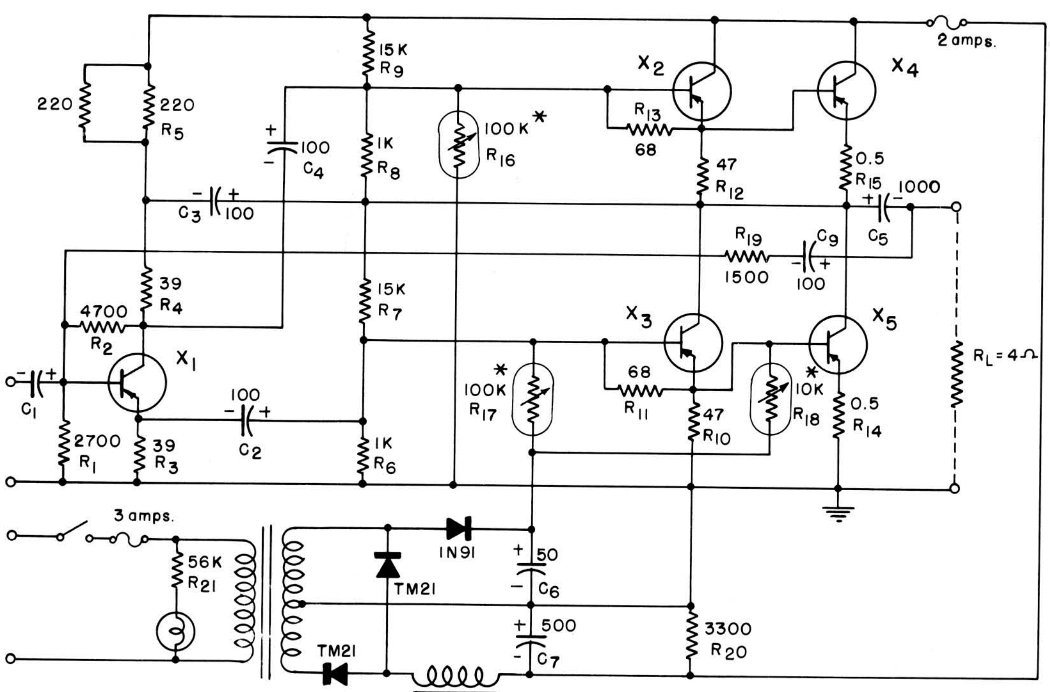
*Series Amplifier*

The schematic of a series circuit capable of 45 watts output is shown in Fig. 2. The circuit uses all transistors of like conductivity (p-n-p in this case, because of their availibility) and requires no driver or output transformers. The series amplifier consists of a split-load phase inverter, capacitance-coupled to a class-B common-collector driver. The driver stage is direct-coupled to the class-B common-emitter power output stage. The driver and output stages each are in series for the d-c collector supply.

The amplifier is convection cooled and weighs about 10 pounds; it is similar in size and appearance to the quasi-complementary-symmetry amplifier stage, shown in Fig. 5. This model uses RCA 2N301 and 2N301A transistors throughout and can deliver 45 watts to a 4-ohm load up to an ambient temperature of 50 degrees. Performance characteristics for the amplifier are given at the end of the discussion.

Power Output Stage

The series circuit, shown in Fig. 2, uses two p-n-p transistors, each operating common emitter, in the output stage (RCA-2N301A) and delivers its power by capacitive coupling into a 4-ohm load. The output transistors were selected for this application because of their low junction-to-case thermal resistance (<1.5°C/watt), their high-current gain at collector currents of about 4 amperes, and their relatively high collector-emitter breakdown voltage. (The importance of these properties is discussed in the Appendix.) This circuit operates class B, and, with oppositely-phased voltages applied to the bases of the output transistors, the a-c collector currents add in the load; hence, these transistors are in series for the d-c collector supply (the voltage appearing across $X_3$ and $X_5$ is approximately one-half the supply voltage) and in parallel for the a-c signals. Since this circuit does not require an output transformer, the amplifier size and weight are materially reduced, while the efficiency of power transfer to the load is improved. The




NOTE:
All resistances in ohms
All capacitances in μf,
unless otherwise specified
K = 1000

* = Thermistor value at 25°C.

$X_1$ = RCA 2N301

$X_2, X_3, X_4, X_5$ = RCA 2N301A

TM21 = Transitron silicon rectifier

Fig. 2 - Schematic of 45-watt series amplifier.

0.5-ohm resistors in series with the emitter of each output transistor improve the d-c circuit stabilization and also reduce distortion but at the expense of a slight decrease of power gain and power output. The overall collector conversion efficiency (including the power lost in these resistors) is still about 65 percent at maximum power output.

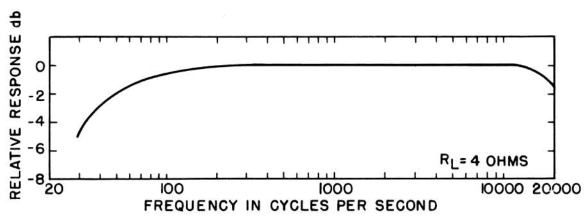



Fig. 3 - Frequency response of 45-watt series amplifier.

The frequency response of the amplifier is shown in Fig. 3. The high-frequency response is limited by the beta (common-emitter current gain) cutoff frequency of the transistors, and is highly dependent on the source impedance and the $r_{bb}'$ of the transistors. The best frequency response for a common-emitter stage is obtained when it is driven from a low source impedance. It is therefore also desirable that $r_{bb}'$ be as low as possible. The 2N301 and 2N301A transistors used have an $r_{bb}'$ of about 30 ohms. The preceding stage, being common-collector, provides a low source impedance for the output stage. The low-frequency response is limited mainly by coupling capacitor $C_5$ because of the low output and load impedances involved.

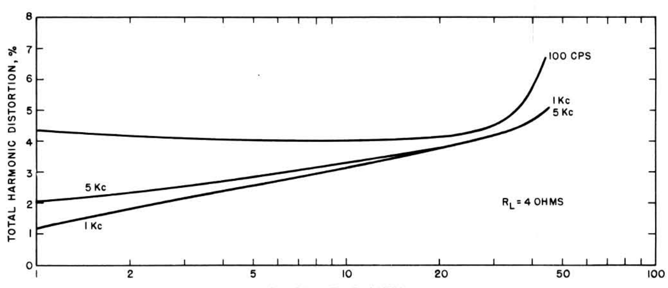



Fig. 4 - Distortion versus power output for 45-watt series amplifier.

To obtain the distortion characteristics shown in Fig. 4 the power transistors should have a large-signal current gain of at least 25, at 4 amperes of collector current. With a 4-ohm load, peak collector currents in the order of 4 to 5 amperes will be present at rated output. This distortion may be reduced at the lower frequencies by increasing the capacity of the coupling capacitors.

An equally important property of the output transistors in this circuit (Fig. 2) is their transconductance ($I_C$ versus $V_{BE}$). Since the output impedance of the driver stage is relatively low, the output transistors are essentially driven from a voltage source. Therefore, variations of transistor transconductance become important. For distortion considerations, the transconductances should not vary more than 2 to 1.

The output transistors dissipate about 9 or 10 watts each, under the worst sine-wave condition (40 percent maximum output), and are cooled both by convection and radiation from the large surface area obtained from the ribbed-chassis configuration. Since the transistors are above chassis potential, they are fastened to the chassis with plastic bolts and insulated with 1-mil Mylar coated with silicone oil. The thermal properties of this circuit are discussed in the Appendix.

## Series Driver Stage (Fig. 2)

The driver stage also used p-n-p transistors (RCA 2N301A) and is connected in an emitter-follower configuration (common collector). This class-B stage is direct-coupled to the output transistors. Direct coupling eliminates the requirement for large coupling capacitors which ordinarily would be necessary because of the low impedances involved. Direct coupling also has the advantage of eliminating that crossover distortion in the output stage which could occur since the charge and discharge paths of the coupling capacitor would be different. This difference would cause a reverse d-c bias to be applied to the bases of the output stage which would then be dependent upon the signal level and would result in increased distortion, since it would negate the forward-bias normally applied between emitter and base used to minimize crossover distortion. The problem of crossover distortion which might be caused by coupling capacitors $C_2$, $C_3$, and $C_4$ is greatly reduced in the driver stage by the use of resistors $R_{11}$ and $R_{13}$, each connected between the base and emitter. The effect of these resistors[3] is to linearize the input impedance of of driver stage by presenting a relatively constant input impedance to the phase inverter, both during conduction and non-conduction. With a discharge path provided for the capacitors during the non-conducting part of the cycle, the tendency for a charge to develop on the capacitor and produce crossover distortion is reduced.

If the large-signal current gains of the output transistors are above 25 (at peak signal), the drivers supply about 400 to 500 milli-amperes of peak current at full power output. This peak current requirement is easily satisfied by the driver transistors. (Lower power transistors could be used if available.)

[3] *LB-1022 Transistor Audio Amplifiers.*

Phase Inverter and Driver Stages

Transistor $X_3$ (2N301) is used as a split-load phase inverter which feeds driver transistors $X_2$ and $X_3$. This stage operates class A and is biased at approximately 160 milliamperes collector current, with 35 volts between the collector and emitter to provide sufficient signal to the driver stage without introducing clipping at maximum power output. With no signal, this transistor then dissipates about 5.5 watts and is thermally attached to the chassis which acts as the heat dissipator.

Resistors $R_3$ and $R_4$ ensure a low source impedance for the driver transistors. The impedance (for transistors of similar characteristics in the upper and lower halves) presented by the upper half of the driver output transistor combination is essentially equal to that presented by the lower half, since, in each case, there is a common-emitter stage preceeded by a common-collector stage. This means that variations in the load impedance will be reflected to the phase inverter in the same ratio for the upper and lower halves and the amplifier will thus be in balanced operation. By virtue of splitting the collector load, and feeding the upper half of the amplifier from $R_4$, an essentially balanced output voltage is obtained.

Inherent negative feedback exists in the amplifier by virtue of the phase splitter configuration, the common-collector driver stage (100 percent negative voltage feedback), and the unbypassed emitter resistors in the output stage. In addition, 8 db of negative feedback is applied through resistor $R_{19}$ in series with capacitor $C_9$ around the entire amplifier (Fig. 2.) (The amplifiers should be driven from a source having an impedance of about 500 ohms.) The phase inverter is bootstrapped from the output through capacitor $C_3$, which enables the upper half of the amplifier to swing to the full collector supply voltage. Without this arrangement, the signal would clip on peaks for the upper half and would lead to lower collector efficiency for the driver and output stages, in addition to reducing the available undistorted power output.

The input impedance of the amplifier is about 113 ohms and the amplifier provides a power gain of about 30.6 db at maximum signal output.

Bias Consideration for the Driver Output Stages

In order to eliminate the effects of crossover distortion caused by the non-linear transfer characteristics of transistors at low signal levels, a small forward quiescent d-c base-emitter bias voltage is required. Optimum bias voltage is obtained for the driver stages by the voltage divider action of resistors $R_8$ and $R_9$ in conjunction with $R_{12}$ and $R_{13}$ for the upper transistor and resistors $R_6$ and $R_7$ in conjunction with $R_{10}$ and $R_{11}$ for the lower transistor. At room temperature (28°C) the quiescent current for the driver stage is about 8 milliamperes. Bias for the output transistors is then obtained from the voltage drop across the emitter resistors $R_{10}$ and $R_{12}$ which are in series with the emitters in the driver stage. This bias is strongly dependent upon the quiescent current of the driver stage and the voltage divider network previously described. Quiescent current in the output stage is about 50 ma at room temperature.

As ambient temperature is increased, the operating points of the driver and output stage change, since both the saturation current and the input conductance increase[4]. The problem of d-c stabilization for the output stage is further complicated by virtue of direct coupling of the driver output stages. As temperature increases, the driver $I_{CO}$ increases, thereby increasing the forward voltage bias for the output stage. Simultaneously, the output transistor $I_{CO}$ is increasing and causes the quiescent current on the output stage to further increase. The 0.5-ohm resistors, $R_{14}$ and $R_{15}$, in the output stage aid in stabilization of this stage by providing a negative current feedback which tends to maintain the output quiescent collector current constant. In the common-collector driver stage, degenerative direct-current feedback is obtained by virtue of resistors $R_{10}$ and $R_6$ in the lower transistor, and resistors $R_{12}$ and $R_8$ for the upper transistor.

The d-c operating point of the output stage is further stabilized by use of thermistor compensation. Thermistors, $R_{16}$, $R_{17}$, and $R_{18}$ are connected in the circuit to provide a base-to-emitter voltage for the driver transistors which decreases with temperature. (These thermistors are mounted on the chassis near the output transistors to compensate more closely the change in junction temperature rather than ambient temperature). This action tends to maintain the driver emitter current constant with temperature.[4] A positive bias supply is used to compensate the transistors at higher temperatures since it is actually necessary to apply a reverse bias to the base-emitter junction to maintain a relatively constant operating point at elevated temperatures. In this manner the tendency for the quiescent collector current in the output stage to change with temperature is reduced, with the result that the amplifiers perform satisfactorily throughout a temperature range of -10°C to +50°C. At low temperatures, cross-over distortion is increased because of the inability of the thermistor networks to adequately compensate the output transistors.

Power Supply

The power supply requires about one-half the volume of the amplifier. This is because the high average

[4]*LB-979, Temperature Effects in Circuits Using Junction Transistors.*

current (required to obtain 45 watts power output directly into a 4-ohm load) makes filtering difficult and requires the use of a choke in the circuit. The supply consists of two silicon rectifiers in a full-wave circuit and a choke-input filter which provides good filtering and regulation. The forward resistance of the silicon rectifiers is only 1 ohm and the transformer and choke have low-resistance windings which aid the regulation. An additional positive supply for bias stabilization is derived from a 1N91 diode half-wave rectifier. The no-load voltage for the collector supply is about 58 volts and drops to about 45 volts at full power output. The ripple in the load with maximum signal is -15 dbm.

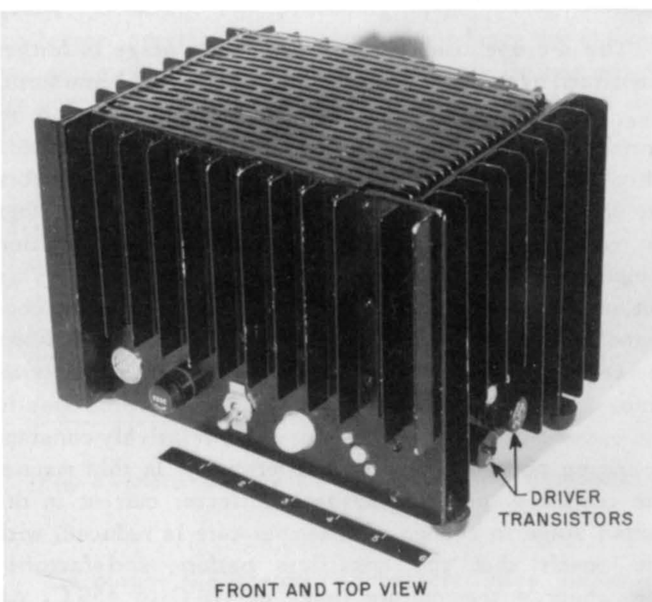
*Quasi-Complementary Symmetry Amplifier*

The second type of high-power amplifier investigated was the quasi-complementary symmetry circuit which was based on the 6-watt amplifier described in LB-1027.[5] A 45-watt convection-cooled amplifier was designed and constructed which operated satisfactorily over a temperature range of -10°C to +50°C. A photograph of the amplifier is shown in Fig. 5, and the circuit schematic is shown in Fig. 6.

$X_2$ and $X_4$ operate as common-collector amplifiers. When these transistors are conducting, the output current is $B_2 B_4$ times the current supplied by the class-A driver stage, where $B_2$ and $B_4$ are the effective current gains of the phase-splitter and output stages. Similarly, the output current when $X_3$ and $X_5$ conduct is $B_3 B_5$ times the current supplied by the class A driver, where $B_3$ and $B_5$ are the effective current gains of the phase-splitter and output stages. If $B_2 B_4 = B_3 B_5$, the input resistance presented to the first stage is equal to $B_2 B_4 R_L$, and the circuit is in balanced operation.

Output Stage

The output stage uses two RCA 2N301A power transistors (selected for low thermal resistance, <1.5°C/watt) connected in series with the d-c supply. The quiescent d-c operating point ($I_C$ = 70 ma at 25°C) is determined by the voltages across $R_7$ and $R_8$. These voltages are obtained from the voltage drop across $R_4$ and $D_1$ and $D_2$. $D_1$ and $D_2$ are developmental RCA TA-134 temperature-compensating diodes which act to maintain the quiescent operation point of the driver transistors constant with temperature, (by providing a reduced



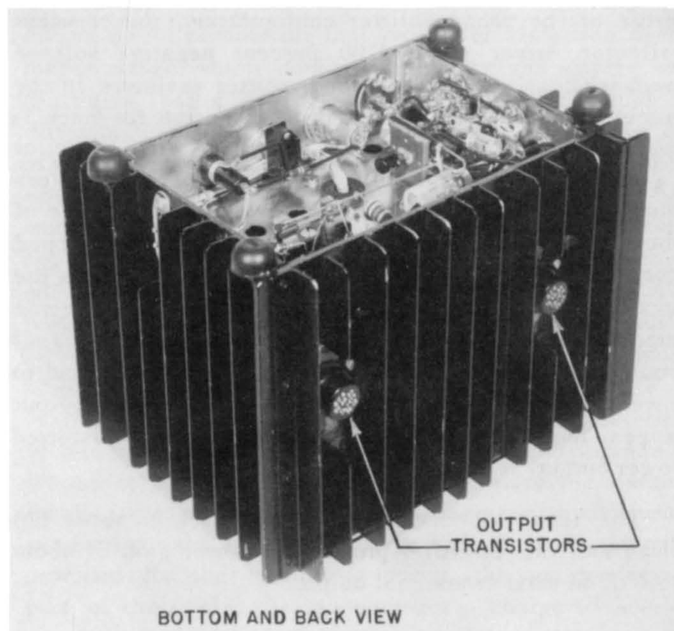




**Fig. 5 - Photograph of 45-watt quasi-complementary amplifier.**

The 45-watt power amplifier consists of a p-n-p class-A driver, a complementary transistor pair which acts as a phase-splitter, and the power output stage which consists of two p-n-p transistors connected in a single-ended push-pull output, capacitance-coupled to a 4-ohm load. The last two stages operate class B.

[5] *LB-1027, A Transistor Phonograph Amplifier Using A Quasi-Complementary Transistor Amplifier.*

forward voltage drop with increasing temperature) and thereby increase the thermal stability (thermistors could also be used in place of the diodes). The circuit thermal stability could be increased further by using 0.5-ohm resistors in the emitters of the output stage to provide negative current feedback at the expense of losing some signal power. This loss could be compensated by increasing the supply voltage a few volts. Some signal power is lost (about 1 watt at maximum power

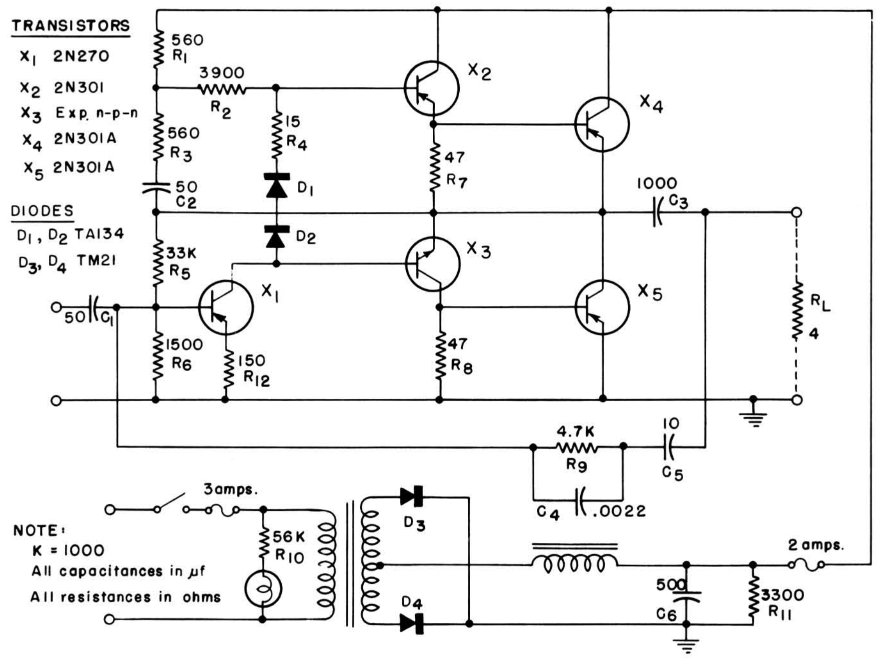



Fig. 6 - 45-watt quasi-complementary amplifier schematic.

output) in resistors $R_7$ and $R_8$, since they are in shunt across the base-emitter junctions of the output transistors which have an input impedance of approximately 20 ohms.

$X_4$ and $X_5$ operate essentially as emitter followers, being driven by $X_2$ and $X_3$, respectively. These transistors were selected so that their collector-to-emitter breakdown voltage exceeded 60 volts, with 47 ohms connected between base and emitter. This insures satisfactory operation in the circuit at higher temperatures as discussed in the Appendix.

## Complementary Phase-Splitter Stage

$X_2$ is a p-n-p 2N301A transistor and $X_3$ is an n-p-n transistor (RCA experimental transistor). Each operates class B and serves to split the phase of the incoming signal from $X_1$. These transistors also operate essentially common collector, and, therefore, present a high input impedance to the driver stage. Because of the voltage drops in two cascaded common-collector stages, the output-voltage swing is limited to a value less than the supply voltage. To allow the peak signal swing to approach the value of supply voltage, 1 db of positive feedback is applied, (bootstrapping) by way of $C_2$ and $R_3$, across $R_1$. By obtaining the correct amount of feedback, and permitting a maximum voltage swing in the output stage, the efficiency of this stage was increased to about 70 percent, at room temperature.

The harmonic distortion of the amplifier for various power outputs is shown in Fig. 7. Distortion increases at higher power output because of the increased nonlinearity of the transistors at high collector currents. At very low power outputs, the distortion increases slightly because of the fact that the amplitude of the nonlinear crossover region is becoming comparable to the peak signal swing. Distortion increases at low frequencies and high power output since the load line is eliptical due to $C_3$. At higher frequencies, transistor phase shift (because of the low cutoff frequency) causes nonlinearity and increases distortion.

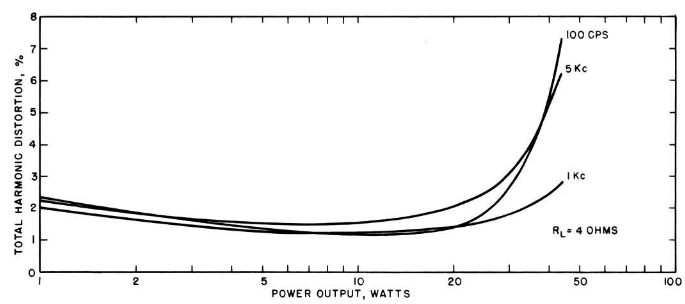



Fig. 7 - Distortion versus power output for 45-watt quasi-complementary amplifier.

The frequency response of the amplifier is shown in Fig. 8. The 3-db points are at about 50 cps and 14 kc. The high-frequency cutoff is limited by the relatively low beta cutoff frequencies of the power transistors (units ranged from 4 kc to 10 kc), and is strongly dependent upon the source resistance. Because of the low value of load resistance (4 ohms), the lower half fo the amplifier actually operates somewhere between common-collector and common-emitter operation. The low-frequency response is limited by the coupling capacitors $C_1$ and $C_3$.

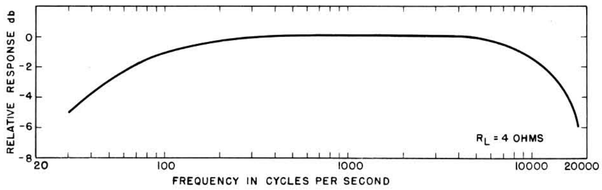



**Fig. 8 - Frequency response of 45-watt quasi- complementary amplifier.**

## Driver Stage

Transistor $X_1$ is a medium power unit (RCA 2N270) which acts as a class-A driver. At room temperature (25°C), about 7 milliamperes of collector current (providing an optimum operating point) flows through diodes $D_1$ and $D_2$ which provide d-c bias for the following stages. (Two diodes are used since the voltage developed across them is dependent upon the direct current flowing and it is necessary to develop about 0.35 volt to minimize cross-over distortion in the following stages.) For this reason, the temperature stability of this stage is important. The transistor is biased through resistor $R_5$ which is connected to the midpoint of the output stage, and thereby provides both d-c and a-c negative feedback. Stability is further increased by virtue of emitter resistor $R_{12}$ which provides negative current feedback in conjunction with $R_6$.

A negative feedback of 9 db is provided around the entire loop to the base of $X_1$ through $R_9$. $C_4$ is connected in parallel with $R_9$ to give a step-response in the feedback loop for stability.

At full power output, the power gain of the amplifier is 41.8 db. The input impedance of the amplifier is about 200 ohms at 1000 cycles

## Power Supply

The power supply in this amplifier is similar to that of the 45-watt series amplifier. Full-wave rectification is obtained with silicon rectifiers followed by a choke-input filter. At full-signal output, the direct current is approximately 1.6 amperes at about 41 volts. The quiescent direct current at room temperature is about 70 ma, with a no-signal voltage of about 54 volts.

### *Complementary-Symmetry Amplifiers*

The property of symmetry which exists between p-n-p and n-p-n transistors permits the design of a wide variety of symmetrical circuits. Several types of transformerless class-B circuits have been designed which are capable of low or medium power output.[3,6] Although no high-power complementary amplifiers have been constructed, because of the lack of n-p-n transistors which are capable of high dissipations, nevertheless it is possible to predict the performance of high-power amplifiers by extrapolating the results of the design of lower power circuits together with the information obtained from the design of the series and quasi-complementary amplifiers.

Many of the problems encountered in the design of both the series amplifier and the quasi-complementary amplifiers also arise in designing complementary-symmetry amplifiers. The device, bias, and thermal considerations for these amplifiers are similar, and are covered in other sections of this bulletin. One complementary-symmetry circuit configuration which could easily be adapted to operate as a high-power amplifier is the 5-watt amplifier discussed in reference 3. This circuit is similar to the quasi-complementary circuit in both the method of obtaining bias and in the use of positive and negative feedback. The power stages of the complementary circuit are shown in Fig. 9. As in the quasi circuit, no phase inverter is required, nor are any input or output transformers used. Temperature-compensating diodes could be used to replace thermistor $R_{16}$, and thereby provide better tracking for the compensation. Since no signal power is lost in resistors $R_{20}$ and $R_{21}$, these could be replaced by thermistors in order to provide a temperature-compensating bias for the output stage and thereby greatly increase the thermal stability of this circuit over that of the series or quasi amplifiers.

A high-power complementary amplifier could consist of two common-collector stages and a class-A driver stage, similar to that shown in Fig. 9. The supply voltage would be as high as the transistor breakdown voltages would permit. In order to obtain high power output, the load resistor should be reduced to as low a value as practical, the limit being the transistor peak collector current ratings, the permissible distortion, or the transistor dissipation ratings.

The inherent symmetry of the amplifier provides balanced operation. Requirements for matching the output transistors are materially reduced, since both class-B stages operates as common-collector amplifiers; therefore, the advantage of inherent negative feedback is present. Also, for this same reason, the frequency response of this circuit should be higher than that for the quasi and series circuit (using equivalent transistors.)

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[6] *LB-1021, Design Considerations in Class-B Complementary Symmetry Circuits.*

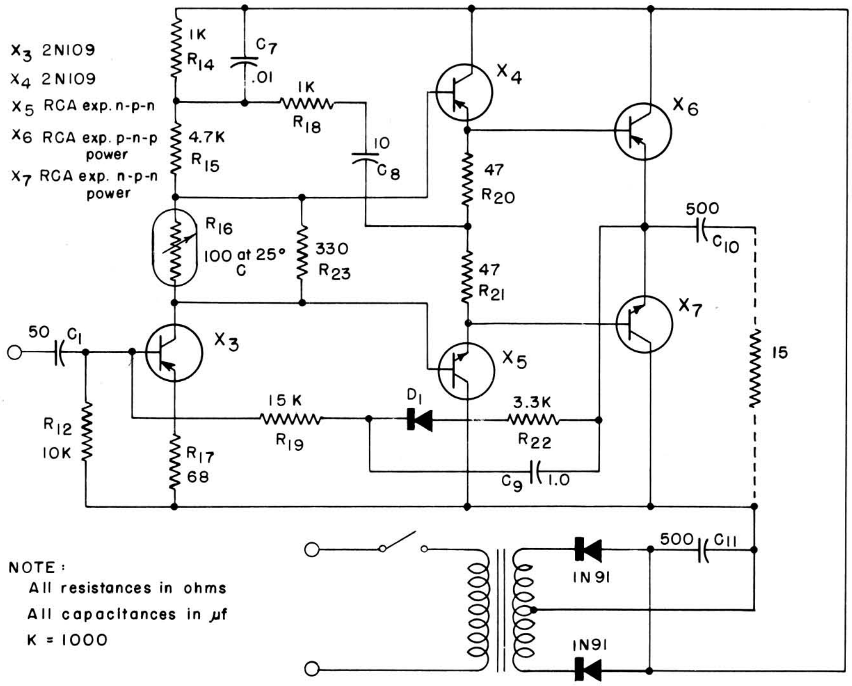


Fig. 9 - Power stages of 5-watt complementary symmetry amplifier.

**TABLE I**

| Comparison of 45 watt Series and Quasi Amplifiers | | |
|---|---|---|
| Characteristics | Series Amplifier | Quasi-Complementary Symmetry Amplifier |
| Input Resistance | 113 ohms | 200 ohms |
| Load Resistance | 4 ohms | 4 ohms |
| Source Resistance | 400-600 ohms | 400-600 ohms |
| Output Resistance | 2.5 ohms | 1.6 ohms |
| Power Gain | 30.6 db | 41.8 db |
| Frequency Response | Fig. 3 | Fig. 8 |
| Harmonic Distortion | Fig. 4 | Fig. 7 |
| Negative Feedback | 8 db | 9 db |
| Average Collector Current in Output Transistors | | |
| Idling | 50 ma | 70 ma |
| Maximum Output | 1.55 amperes | 1.6 amperes |
| Hum (at maximum output | -15 dbm | -15 dbm |
| Weight | 10 pounds | 10 pounds |
| Size | 8 1/2x6 1/2 x6 1/2 inches | 8 1/2x6 1/2 x6 1/2 inches |

*Comparison of These Circuits*

At this point, it is desirable to compare the series, quasi-complementary, and complementary-symmetry amplifier circuits and to examine the advantage and disadvantages of each. The characteristics of both the series and quasi-complementary amplifiers are summarized in Table I.

One advantage of the series amplifier is that it employs all like-conductivity power transistors. For this reason, however, a phase inverter is required to obtain push-pull amplification. Associated with the phase inverter is a small loss in amplifier power gain, and the required use of capacitors to obtain coupling to the following driver stage. Direct coupling cannot easily be employed because of the difficulty in obtaining proper bias for the following stages. Both temperature compensation and stabilization are required, in addition to a positive bias supply (for temperature compensation) in order to obtain satisfactory operation to about 50°C.

The quasi-complementary amplifier requires one complementary transistor pair in the driver stage and transistors of like conductivity in the output stage. Because of the complementary action of the driver stage, no phase inverter is required. This facilitates the use of direct coupling throughout the three stages of the power amplifier. Because of the direct coupling, however, temperature changes in one stage strongly affect the temperature stability of the following stages. This effect may be minimized to a large extent by stabilization and compensation; however, as previously explained, the output stage is still susceptible to temperature changes unless additional power consuming techniques (such as emitter resistors, etc.) are employed.

Complementary-symmetry amplifiers are truly symmetrical; they require no phase inverter and can be direct coupled, thus eliminating the need for coupling capacitors. Also, they can be more readily stabilized than the other two amplifiers previously mentioned.

In conclusion, it appears that subsequent high-power amplifiers should employ a complementary-symmetry circuit. This type of circuit has no major disadvantage and lends itself to straightforward design from the standpoint of power output and thermal stability.

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## APPENDIX I

### Device Considerations for High Power Operation

In a transistor power amplifier, the load impedance is rarely matched to the transistor output impedance. Instead, the load impedance is selected so that the load line will traverse the maximum usable area of the collector characteristics without exceeding maximum ratings. The maximum power output is equal to one-half the product of the collector-emitter voltage and the peak current. To obtain a higher output power, it is necessary to increase the peak current (by using a lower load impedance) or to increase the collector-emitter voltage, or both. Thus, the maximum voltage and current ratings, together with the maximum allowable dissipation which is limited by thermal stability (next section) determine the maximum obtainable output power.

The maximum collector current is generally specified by the transistor manufacturer. It is usually limited by the fact that the current gain of the transistor has decreased to such a value at high currents that the device no longer has sufficient gain for satisfactory circuit operation with the result that the distortion increases to an intolerable level. A limitation might also be imposed since the junction may not be a perfectly flat surface and excessive currents may result in overheating which would produce "hot spots" in the junction.

Raising the collector voltage to increase the power output usually results in less distortion than arises from raising the load current. In transformerless amplifiers of the type discussed in this bulletin, the peak inverse voltage is twice that applied to each transistor, and is equal to the total supply voltage (for maximum voltage swing). The maximum collector voltage which may be applied to the transistor is usually limited by the avalanche breakdown (or sometimes punchthrough).

In practical class-B circuits, the output stage will usually be connected either in a common-emitter or a common-collector configuration. For either connection, the breakdown voltage will be lower than that measured for the common-base connection, and will be a function of the d-c resistance connected between the emitter and base of the transistor. For this reason it is important to insure that the breakdown voltage measured under *actual circuit conditions* (with the particular $R_{BE}$ in the circuit) is not exceeded. Fig. 10 shows a plot of the breakdown voltages for some p-n-p power transistors with various resistances connected between the base and emitter. It may be seen that the highest breakdown voltages are obtained with the base tied directly to the emitter ($R_{BE}$ = 0). As the base-emitter resistance is increased, the breakdown voltage decreases until it becomes fairly constant for a resistance of about 1000 ohms. Thus, in order to enable the transistor to operate with a higher collector voltage, it is desirable to operate the unit with a low base-to-emitter resistance. (In both the series and quasi amplifiers, the $R_{BE}$ employed was 47-ohms).

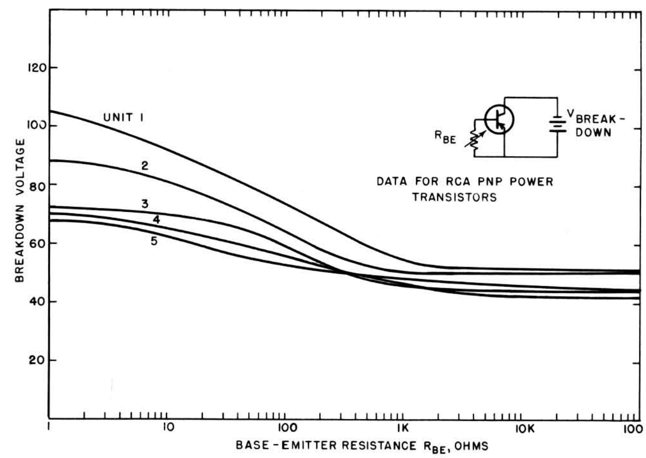


**Fig. 10 - Collector-emitter breakdown voltage versus base-emitter resistance.**

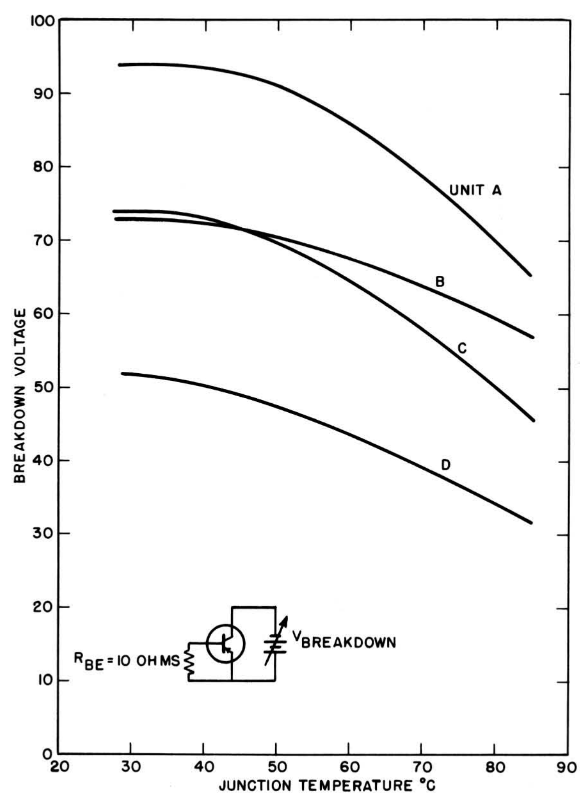


**Fig. 11 - Collector-emitter voltage breakdown versus temperature.**

Unfortunately, as the junction temperature is increased, this breakdown voltage is further reduced as shown in Fig. 11. In some of the transistors, at junction temperatures of 85°C, the breakdown voltage is reduced by almost 40% of its room-temperature value. This is due partially to increased beta at higher temperatures and partially to increased $I_{CO}$. In any event, it may be seen that even with low values of $R_{BE}$ in the circuit, the effects of increased junction temperature cannot be ignored. When designing high-power transistor amplifiers, it should be remembered that the junction will usually be operated at a high temperature, because of the high transistor dissipation and/or high ambient temperature. Therefore, this reduction in breakdown voltage must be taken into consideration in the determination of the maximum safe collector voltage for the transistor.

When an amplifier is driven from a source impedance much lower than its input impedance (which is often the case in a power amplifier), distortion may arise due to the non-linearity of the transconductance characteristic (collector current versus base-to-emitter voltage). Distortion may be caused by excessively low or excessively high currents. At high collector currents the transfer characteristic becomes more nonlinear as a result of a decrease in beta. At low collector currents, it is quite nonlinear as a result of the nonlinear input impedance at these levels. This condition may lead to crossover distortion in a class-B amplifier.

To minimize the crossover distortion for class-B amplifiers, which can be quite severe for small (or even medium signals), it is necessary to apply a small amount of forward bias to the base-emitter junction. This establishes a d-c operating point for the emitter current and collector voltage. Since the transistor is a temperature-dependent device, this operating point will shift as the temperature is varied. This change of operating point is due to both the changes in the transistor saturation current and the d-c input conductance.[4] As the junction temperature is increased, the quiescent collector current will increase for a fixed bias since both the saturation current and input conductance will rise. (The change in input conductance produces a variation in collector current which is important over the entire temperature range. The change in $I_{CO}$ becomes important only at high temperatures.) This condition may be aggravated further if the output stage is operated in a common-emitter configuration, and the bias applied to the base-emitter junction is fixed, since the changes in $I_{CO}$ (saturation current plus leakage current) and input conductance will be amplified by the effective d-c beta of the transistor.

A transistor operating at high ambient temperatures and/or high dissipations will tend to draw more collector current as the collector junction temperature rises. As explained in Appendix II, this condition may be cumulative and lead to thermal regeneration and eventually the unit will be destroyed. Therefore, it is desirable to maintain the d-c operating point stable with temperature changes to minimize thermal regeneration. The amplifiers described in this bulletin use various techniques in order to reduce the effect of temperature changes upon overall performance.

For class-B circuits, the technique of temperature stabilization is limited because the collector and emitter currents are dependent upon signal level and consequently are not constant. Therefore, d-c feedback cannot be applied easily. A fair degree of d-c stabilization may be obtained by placing small unbypassed emitter resistors in the output stage; however, a-c power will be lost in these resistors, since they cannot be capacitively bypassed without introducing crossover distortion. The effect of these resistors in the series circuit is discussed in Appendix II which compares their contribution to thermal stability to the a-c power lost in these resistors.

By far the most effective means of maintaining stable d-c operating points in class-B circuits are the temperature-compensation techniques. When these techniques are applied, it is well to remember that the temperature change which should be compensated for is the junction temperature, and not the ambient temperature. Therefore, it is important that the compensating device be tightly coupled (thermally) to the transistor to be compensated. In this case, the compensating element will follow rather closely any changes in the transistor mounting-base temperature, which for the majority of power transistors (units with low thermal resistances) will satisfactorily compensate the device for reasonably high temperatures.

In order to compensate a transistor against moderate temperature rises, the d-c bias voltage which must be applied between the base and emitter should decrease approximately 2.0-2.5 millivolts per degree centigrade increase in junction temperature (for germanium transistors) in order to maintain the emitter current constant. This will compensate for the change in input conductance. The compensation circuit should be such that it will supply optimum bias over the temperature range desired. With tight thermal coupling of the compensating elements to the transistors, temperature rises due to dissipation can also be satisfactorily handled. At higher junction temperatures, (about 50°C to 60°C) the effect of the increase of saturation current will become important and simple compensation will become less effective. In some circuits, it may be necessary to add an external bias circuit of reverse polarity in order to control the transistor at very high junction temperatures. (This compensates in part the forward voltage bias developed across the intrinsic base emitter junction which results from the voltage drop across $r_{bb}'$ caused by $I_{CO}$.) Examples of the latter are the series circuit described previously and the 5-watt amplifier transformer-coupled to the load described in reference 3.

The proper temperature compensating bias voltage may conveniently be obtained by using a thermistor, a germanium diode, or a transistor in a resistive network, to provide a curve of network resistance versus temperature which approximates that required to compensate for the shift of the transistor transfer characteristic over the required operating temperature range. The RCA developmental TA-134 diode, for example, is designed primarily for temperature and voltage compensation in class-B circuits using transistors such as the 2N301 audio power-output transistor. As described in reference 4, diode compensation can be much more effective than thermistor compensation, because the diode can be constructed from the same material as the transistor and thus will follow more closely any change in the transistor temperature.

It should be noted that even with the advent of silicon or intermetallic transistors, which will increase the allowable junction temperatures to much higher values, the temperature problem will not be alleviated. In all likelihood it will become more severe since the requirement for high-temperature circuitry is becoming more important for many applications, particularily to the military. For this reason, the available devices will probably be operated near their maximum junction temperature, and temperature compensation and stabilization will be required for stable operation. Because of the extended temperature range, it will probably become even more difficult to develop stable circuitry. However, with some further refinements, most of the techniques available for stabilization and compensation of germanium transistors should be applicable for these higher-temperature units.

## APPENDIX II

### Thermal Considerations In Transistor Power Amplifier Design

*General*

The problems of transistor dissipation and heat removal in a high-power transistor amplifier are a major consideration. It is therefore desirable to review the important considerations involved in operating a transistor at high dissipations and correspondingly high junction temperatures.

The two basic thermal conditions for stable, safe, reliable operation of a power transistor are as follows:

1. the maximum rated junction temperature should not be exceeded.
2. a criterion for circuit thermal stability is

$$\frac{dP_D}{dT_J} < \frac{1}{\theta_T} \qquad (1)$$

and should be satisfied where:

$P_D$ = total transistor power dissipation in watts

$T_J$ = temperature of the collector junction in °C

$\theta_T$ = thermal resistance of the entire thermal path in °C/watt

(The basis for this criterion is discussed in another part of this section.)

Before discussing these two conditions in further detail, a discussion regarding thermal resistance and its effect on junction temperature is in order. The process of heat transfer may be more readily understood by the electrical engineer if an electrical analogy is presented. This analogy may take many forms depending on which terms in heat transfer are made equivalent to their electrical analogy. The analogy to be used in this bulletin is presented below:

| Thermal Quantities | | Electrical Quantities |
|---|---|---|
| Rate of Heat Flow, q (watts) | ⟷ | Current, I |
| Temperature, T (°C) | ⟷ | Voltage, E |
| Thermal Capacity, C (watt-sec/°C or joules/°C) | ⟷ | Capacity, C |
| Thermal Resistance, $\theta$ (°C/watt) | ⟷ | Resistance, R |

The thermal resistance is then the resistance to the flow of heat, whether it be by conduction, convection, radiation, or any combination of these. Thermal resistance is the quantity which causes a temperature gradient to be present when heat is transferred from one area to another.

A junction power transistor is diagramatically shown in Fig. 12a mounted on a heat sink. The main thermal paths from the junction to the air, or to any other surrounding media, are also illustrated. The corresponding electrical equivalent circuit is shown in Fig. 12b. The thermal capacities shown are dependent upon the mass of the thermal paths and merely act to produce a delay in the temperature rise at the various points in the circuit.

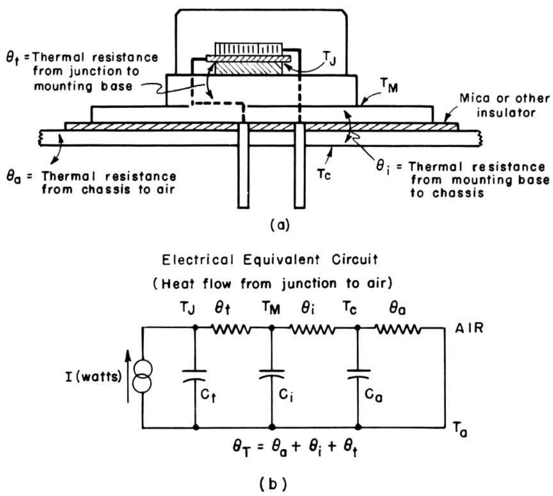


Fig. 12 - Thermal paths for power transistors.

The following definitions apply to Fig. 12b:

$C_t$ depends on the mass associated with the transistor (the junction and internal mounting base) and may be calculated from the physical characteristics of the unit.

$C_i$ depends on the mass of the insulation and usually is small enough to be ignored.

$C_a$ depends on the mass of the chassis or heat sink used to cool the transistor and may be calculated from a knowledge of the size, shape, and material of the sink.

Removal of heat from the junction is dependent directly upon the total thermal resistance from junction to air. Referring to Fig. 12, $\theta_t$ is expressed in °C/watt and represents the resistance to the flow of heat from the junction to the stud or mounting base of the transistor, and is essentially constant for the particular transistor since it is primarily heat transfer by conduction (for power transistors).

Typical values for the various units used in the amplifiers previously discussed are as follows:

| Unit | | Thermal Resistance (°C/watt) |
|---|---|---|
| RCA | 2N301<br>2N301A | 1.0 to 3.0 |
| RCA | Experimental NPN | 3.0 to 6.0 |
| RCA | 2N270 | 50 to 150 |

The 2N270 is a low power transistor, the collector of which is not thermally connected through a mounting stud. Therefore, the thermal resistance, $\theta_t$, will not be constant since the unit is cooled by convection and radiation from the shell, and by conduction through the transistor leads.

The thermal resistance can be easily measured for a particular transistor.[7] $\theta_t$ usually is given by the manufacturer in the power transistor specification sheet. It may be given directly as thermal resistance in °C/watt or as a factor in watts/°C for derating the device. (The derating factor is $1/\theta_t$, or the thermal conductance.

If the transistor must be electrically isolated from the chassis, a thin layer of mica, Mylar, or some other insulation must be placed between the transistor mounting base and chassis. This thermal resistance, $\theta_i$, is constant (heat transfer primarily by conduction) and depends on the thickness and cross-sectional area of the insulator. $\theta_i$ may be reduced by the application of silicone oil between the washer, transistor, and chassis. Silicone oil is an electrical insulator and possesses a higher heat conductivity than air. It is used to fill in the air spaces due to unavoidable irregularities between the contacting surfaces. Typical values of thermal resistance for Mylar insulators (0.001 inch thick and 1 square inch in cross section) with silicone oil are 0.3 to 1.0 °C/watt. Without the silicone oil, this resistance has measured as much as 4 to 6 °C/watt.

It is quite difficult to separate the effect of radiation and convection in the cooling of the fins or chassis to which the transistor is mounted. For this reason it is usually more convenient to deal with the overall thermal resistance of the heat sink to air. (Radiation is quite important in the transfer of heat for transistor cooling and for this reason, it is a good practice to paint the chassis or cooling fins a flat black to improve their emissivity.)

$\theta_a$ (Fig. 12b) represents the thermal resistance from the chassis or other heat sink to the air, or any other media which must act as the final dissipator of heat. This quantity is the most variable in the total thermal

[7] *RB-30 Equipment For Measuring Junction Temperature of an Operating Transistor.*

resistance since it is dependent on the quantity of heat which can be conducted throughout the chassis area and then convected or radiated to the air. The designer may be able to control this quantity by constructing the equipment with large chassis areas which will effectively transfer the heat from the transistor to the air.

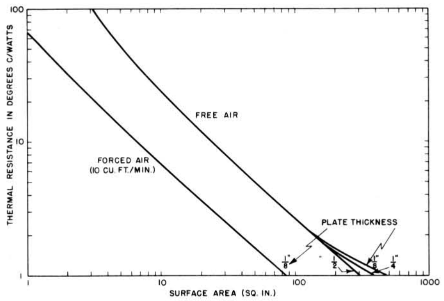


**Fig. 13 - Approximate thermal resistance for convection cooling versus area.**

Fig. 13 shows an approximate relationship between the heat-sink surface area and the resultant thermal resistance. Since the curve for free air cooling assumes a square vertical plate in which the heat source is located in the center, the actual thermal resistance with various fin arrangements will vary somewhat from this curve. For instance, a long, narrow plate will certainly have a higher thermal resistance than that indicated. Plate thickness is important only when very low thermal resistance is required, since it would be desirable to have as small a temperature gradient as possible throughout the plate. For fin arrangements where the corners are relatively close to the transistor, the thermal resistance should be slightly lower. (The thermal resistance of the chassis used in the 45-watt amplifiers previously described was measured to be approximately 1.6 °C/watt which agrees fairly closely with the value of 1.7) which was obtained from Fig. 13.

*Maximum Junction Temperature*

The maximum allowable junction temperature is usually specified by the manufacturer and is a basic limitation to allowable power dissipation in the device. This value is determined by life-testing the units at high ambient temperature and/or high junction dissipation, and establishing a rate of failure or a deterioration in electrical performance for a given time versus junction temperature. In other words, the life of the transistor is affected by the junction temperature and power dissipation at which it is operated. At present, not too much data is available from life testing and various manufacturers present different maximum junction temperatures in their specifications. The junction temperature may be determined for a steady-state dissipation by the following equation, assuming the thermal resistances are known. Average power may be used if the junction time constant (defined as the product of the transistor thermal resistance and capacitance; i.e., $\theta_T \times C_t$). is much higher than the period of the signal.

$$T_J = T_a + \theta_T P_D \qquad (2)$$
$$= T_a + P_D(\theta_a + \theta_i + \theta_T)$$

Where:
- $T_J$ = Junction temperature
- $T_a$ = Ambient temperature
- $\theta_T$ = Total thermal resistance from junction to air
- $P_D$ = Total power dissipation in the transistor

For a given ambient temperature and power dissipation, it may be seen that the junction temperature can be reduced by reducing any one of the series thermal resistances. The thermal resistance, $\theta_T$, is the only basic limitation on the minimum obtainable thermal resistance. In circuits where the transistor is operated at high dissipations, it is usually desirable to eliminate any insulator and thereby reduce $\theta_i$ essentially to zero. Furthermore, if the mounting base of the transistor could artifically be kept at a constant temperature (e.g., ambient temperature) then $\theta_a$ would be essentially zero. The last condition implies that the transistor is attached to an infinite heat sink; i.e., one in which all the heat is removed from the transistor mounting base as soon as it is present. This of course, is impossible in a practical case; however, $\theta_a$ could be made small in comparison with $\theta_T$ by forced air, fluid cooling, or other artificial means. The importance of the thermal resistance may further be illustrated by the following example in which it is desired to calculate the allowable transistor power dissipation $P_D$ which will not raise the junction temperature above its maximum safe value, $T_{Jmax.}$

Given:
- $T_a = 55°C$
- $T_{Jmax.} = 95°C$
- $\theta_T = 1.0°C/watt$
- $\theta_a = 3.0°C/watt$
- $\theta_i = 0$ (transistor thermally attached to chassis)

(From Eq. 2)

$$T_J = T_a + P_D(\theta_a + \theta_T)$$

Transposing, and solving for $P_D$

$$P_D = \frac{T_J - T_a}{\theta_a + \theta_T}$$

Substituting the foregoing values,

$$P_D = \frac{95 - 55}{3 + 1}$$

$$P_D = 10 \text{ watts}$$

This example indicates that at an ambient temperaature of 55°C, 10 watts of power could be dissipated in the transistor and still not exceed the maximum allowable junction temperature, 95°C. If the transistor were to be operated at higher ambient temperatures, the allowable dissipation would have to be reduced, or the effective heat sink area should be increased (lower $\theta_a$). Were the chassis area increased so as to make the thermal resistance $\theta_a$ = 2.0°C/watt, 10 watts could then be dissipated at an ambient temperature of 65°C. If $\theta_a$ were further decreased to zero (infinite heat sink), the final limitation on maximum ambient temperature would be the transistor thermal resistance, $\theta_T$.

With $\theta_a = 0$, and for 10 watts dissipation, the ambient temperature could then be 85°C. Correspondingly, if the transistor thermal resistance could be lowered, the allowable dissipation could further be increased. Some compromise is always required when determining maximum ambient temperature, since the required heat sink area could become excessively large to obtain high heat transfer to air.

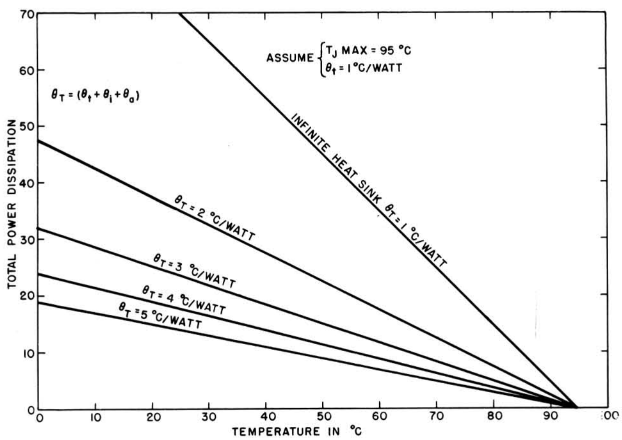


**Fig. 14 - De-rating curve for typical power transistor.**

A curve $[P_D = (T_{J_{max}} - T_a)/\theta_T]$, as shown in Fig. 14, is quite helpful in determining the maximum safe ambient temperature for a heat sink and transistor of known thermal resistances. The example shown is plotted for a power transistor with a maximum junction temperature of 95°C and a thermal resistance of 1.0°C/watt. (This curve can be plotted for any power transistor if the maximum allowable junction temperature and the transistor thermal resistance are known.) The curves may be used to determine the allowable total power dissipation in the transistor for any ambient temperature using a given heat sink. It should be noted again that, where the thermal time constant of the transistor is less than the period of cyclic operation, peak power dissipation should be used rather than average power dissipation.

The uppermost line in Fig. 14 is drawn for the transistor attached to an infinite heat sink; i.e., a transistor in which the surface would remain at a constant temperature equal to the ambient temperature. Although, in practice, an infinite heat sink is not practical, this curve may be used as illustrated below.

Assuming that $\theta_T$ = 3.0°C/watt (heat sink alone would be 2°C/watt), it may be desired to operate the transistor at 15 watts dissipation. Referring to the 3°C/watt curve, it can be seen that the transistor can operate at an ambient temperature of 50°C and still remain within maximum junction temperature rating. If a line is then projected horizontally to the infinite heat sink curve, the transistor stud temperature may be determined; in this case it would be 80°C. If it were desired, a thermocouple could be placed at this point, and the stud temperature measured to check that the actual temperature is not in excess of the value obtained from the curve. As long as this temperature is less than 80°C for 15 watts dissipation, safe operation of the transistor is assured (insofar as maximum junction temperature is concerned) provided the unit is operated within its voltage and current limitations. (This excludes considerations of the thermal stability criterion which will be discussed in the next section.) This might be an alternative method of specifying maximum allowable transistor dissipation; i.e., the unit may dissipate a given amount of power at a maximum mounting base temperature.

*Circuit Thermal Stability Criterion*

The second major consideration for operating a transistor at high dissipation and/or high ambient temperature is the circuit thermal stability criterion. One manner in which this criterion may be expressed is given in Eq. (5) which is derived as follows.

If Eq. (2) is solved for power dissipation, $P_D$,

$$P_D = \frac{T_J - T_a}{\theta_T} .$$

Differentiating this with respect to junction temperature $T_J$,

$$\frac{dP_D}{dT_J} = \frac{1}{\theta_T}\left(1 - \frac{dT_a}{dT_J}\right) .$$

Since the ambient temperature (heat flow from junction to air) is independent of the junction temperature,

$$\frac{dT_a}{dT_J} = 0 .$$

Then

$$\frac{dP_D}{dT_J} = \frac{1}{\theta_T} .$$

The above equation is valid for a circuit which is conditionally stable thermally. The incremental power generated within the device is the *maximum* which may be transferred stably from the device through a heat path to the surrounding media.

Therefore, in order to have a thermally stable circuit, we arrive at Eq. (1) which is repeated below:

$$\frac{dP_D}{dT_J} < \frac{1}{\theta_T} \tag{1}$$

The physical interpretation of this equation may be explained as follows. For an incremental change in junction temperature (perhaps by increasing the ambient temperature), the corresponding *change in total power dissipation (or heat generated) in the transistor should be less than the thermal conductivity* from junction to air ( $1/\theta_T$). This means that the thermal paths from the junction to air must be capable of transfering the incremental increase in heat generation within the transistor to the external heat dissipator.

This criterion is entirely separate from the consideration of maximum allowable junction temperature. The circuit thermal-stability criterion is dependent upon the thermal properties of the transistor and associated mounting (such as type of heat sink, type and location of temperature compensating elements, and stabilization), ambient temperature, the electrical properties of the transistor( current amplification factor, and base lead resistance $r_{bb}'$) and the circuit properties (circuit resistances and operating point). A complete discussion of the factors which influence thermal stability, and therefore determine the maximum transistor dissipation, is given in LB-1056, *"Thermal Stability of Junction Transistors and Its Effect on Maximum Power Dissipation."* As long as the thermal-stability criterion is satisfied, the power dissipation (and/or ambient temperature) can be increased until the maximum allowable junction temperature for the transistor becomes the final limitation.

If the thermal-stability criterion is not met, the rate of heat generation caused by the product of the temperature-dependent component of collector current (which results from the increase of both the collector junction saturation current, and the d-c transfer conductance) and the collector voltage will exceed the capacity of the cooling system. When power is dissipated in the device, the junction temperature is increased. This internal temperature rise causes a further increase in collector current (and therefore dissipation) which further raises the junction temperature. This thermal regeneration will increase and the condition known as thermal runaway will occur because the incremental increase in generated power dissipation will cause a further increase in junction temperature. Of course, under these conditions, the maximum junction temperature will be exceeded since the junction will continue heating up until it is destroyed. However, it should be emphasized that the maximum junction temperature is exceeded because of thermal instability and is not in itself the cause of instability. (A trivial illustration of this fact is that it is possible to design a circuit using a silicon transistor which may be stable at -50°C and become thermally unstable when raised to an ambient temperature of +20°C).

It is complicated to actually calculate the allowable power dissipation and/or maximum ambient temperature at which a transistor *in a circuit* would become thermally unstable, because a knowledge of all the factors described in *LB-1056* which influence the thermal stability is required. It is possible, however, to experimentally determine the maximum allowable power dissipation and/or ambient temperature, and, at the time, gain some insight into the effect of stabilization and compensation upon the thermal stability of the transistor in the circuit.

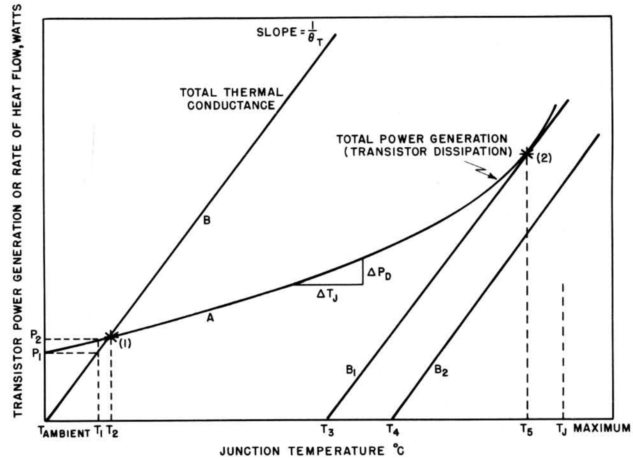


**Fig. 15 - Graphical representation of thermal stability.**

Curve A of Fig. 15 might be a plot of the heat generated at the junction (of a transistor in the power output stage, for example) versus the junction temperature. *This curve is a property only of the circuit and its physical environment.* It is possible to obtain a curve such as this since the temperature of the junction is dependent upon the heat generated within the device. The heat generated is equivalent to the transistor dissipation in watts and is dependent upon the voltages and currents in the transistor. Since most transistor parameters are temperature sensitive, the dissipation will be dependent upon the junction temperature to some extent (depending on the circuit). To obtain curve A, it is only necessary to raise the junction temperature an incremental amount and measure the corresponding change in power dissipation. The slope of this curve is $dP_D/dT_J$.

It is possible to represent the power dissipation capability (rate of heat flow) of the equivalent thermal circuit as a function of the junction temperature of the transistor. The capability for the transistor and heat sink with constant air conditions may be represented by a straight line as shown in Curve B of Fig. 15. Although this straight line is only an approximation of the actual power dissipation capabilities of the equipment (since a non-linear process in involved), any errors introduced by this approximation are favorable to the system and provide a safety factor when this curve is used. This results from the fact that the thermal resistance of the heat sink should decrease slightly where the temperature difference between the junction and ambient are increased. The slope of Curve B may be seen to be $1/\theta_T$, which corresponds to the thermal conductivity of the total thermal circuit from transistor junction to ambient air.

With no voltages applied to the transistor, the unit dissipates no power and thus the junction temperature is the same as the ambient. In Fig. 15, this condition corresponds to the point $T_a$. When voltages are applied to the circuit, the heat generated by the transistor (in the form of dissipation) is $P_1$. This amount of internal heat generation in the transistor requires that the junction temperature increase to $T_1$ (for the cooling facility with a thermal conductance of $1/\theta_T$) in order to permit cooling. Since the junction temperature has now been increased, the total power generated by the transistor must increase to $P_2$. In this manner, the junction temperature and resultant power generation increase until a stable condition is reached at point 1, where the power generation and thermal conductance curves intersect, resulting in junction temperature $T_2$. The path of temperature rise and power dissipation does not actually jump in steps as described above, however, the representation does serve to illustrate the basic influence of one upon the other.

It is now possible to predict the effect on the transistor of changing the ambient temperature. If the ambient temperature were increased, Curve B would be translated to the right, resulting in a higher junction temperature since the intersection of Curve A would be to the right of point 1. If the ambient temperature increased to $T_3$, the junction temperature would be $T_5$. At values of ambient temperature below $T_3$, for this particular thermal conductance, the transistor circuit would always meet the thermal stability criterion, i.e.,

$$\frac{dP_T}{dT_J} < \frac{1}{\theta_T}$$

and is therefore a thermally stable circuit. At ambient temperature $T_3$, curve $B_1$ is tangent to curve A at point 2 where

$$\frac{dP_T}{dT_J} = \frac{1}{\theta_T}$$

Under these conditions, the circuit is conditionally stable since a small incremental increase in junction temperature will cause an unstable condition. A further rise in the ambient temperature, (e.g., ambient temperature $T_4$) will cause the thermal conductance curve $B_2$ to fall below the power generation curve. Under these conditions, the transistor junction temperature cannot stabilize. The power generated within the transistor continues to increase in search of a stable condition until the junction is destroyed. This is a graphic representation of thermal runaway.

If the cooling facility is changed, the result is a change in the slope of Curve B, since effectively $\theta_T$ is changed. If the cooling facilities are reduced, the slope of the thermal conductance curve decreases. Under extreme conditions, the power dissipation curve could fall below the generation curve and result in thermal runaway at relatively low ambient temperatures, since the thermal stability criterion is not satisfied. In many circiuts, where compensating bias is obtained from the temperature changes of the output transistor, the effect of changing the cooling facility would be to alter the shape of Curve A since there is an implicit relationship between the temperature stability of the preceeding stages and the output stage. A better heat sink, or a more effective method of cooling, means that the junction will run cooler for a given ambient temperature because the slope of Curve B will be increased.

We should now examine the curve of transistor internal power generation and investigate the effects of the transistor, circuit, and temperature compensation on the power generated within the transistor. As temperature is increased, both the saturation current and input conductance of the transistor increase, with the result that the d-c operating point (the bias) will tend to shift. For circuits which are neither well stabilized nor compensated for temperature changes, the effect is that the collector (or emitter) current will increase rapidly with temperature, thereby increasing the internal power generated by the transistor. This condition would effectively cause Curve A in Fig. 15 to rise rapidly as a function of junction temperature. The net result of this condition is that only at a higher transistor junction temperature, would the thermal criterion be satisfied.

In Fig. 16, Curves 1, 2, and 3 illustrate the effects of circuit stabilization and/or compensation on the internal power generated by the transistor. Curve 3 might be a plot of power generated in an uncompensated circuit. For a given thermal path from junction to air ($1/\theta_T$), the junction temperature would be equal to $T_3$ at an ambient temperature $T_a$. This circuit would be stable to a maximum ambient temperature of less than $T_4$ since the stability criterion is satisfied only to this temperature (signified by the tangency of the translated thermal conductance curve and Curve 3).

The circuit may be made to perform at a higher ambient temperature (for the same heat sink) by adding stabilization or compensation to the basic configuration. The result is that the tendency for internal power dissipation to increase with temperature is decreased and the circuit might now be described by Curve 2. This circuit could now work in a stable manner up to an ambient temperature of $T_5$, however, the maximum junction temperature would now be exceeded. It is important not to exceed this value of $T_{J_{max}}$ (for the reasons previously discussed) and therefore the maximum safe ambient temperature for this circuit would be somewhat less than $T_5$. This example illustrates a condition where the maximum junction temperature is the limitation on maximum ambient temperature. In the previous case, (uncompensated) thermal runaway occurred far below the maximum junction temperature and this regeneration imposed the limit on the maximum allowable ambient temperature.

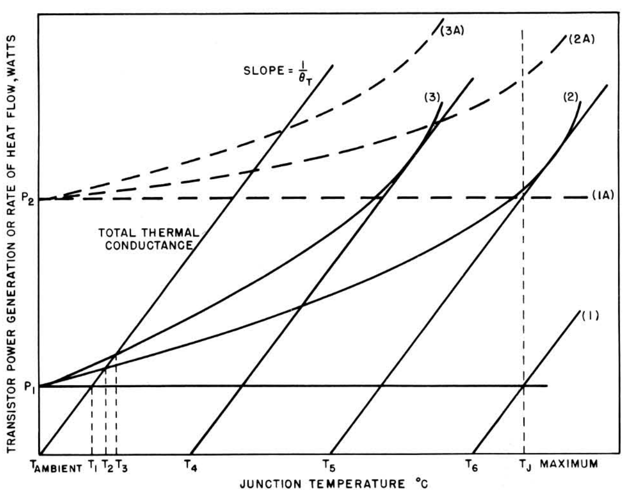


**Fig. 16 - Effect of stabilization and/or compensation on thermal stability.**

If the circuit is further stabilized (operating point maintained nearly constant with ambient temperature), the transistor power generation curve would be further "flattened out". Perfect stabilization and/or compensation would result in Curve 1 which illustrates a circuit where changes in temperature do not effect the operating point (no change in transistor internal power generation). Under this condition, the maximum ambient temperature, $T_6$, would be limited only by the maximum allowable junction temperature since the circuit could exhibit no thermal regeneration.

In all of the above three cases, it would be possible to operate the circuits safely in excess of the calculated maximum ambient temperatures, by providing a more effective heat sink than used in these examples. Once again, the basic limitation of cooling would be the thermal resistance of the transistor itself; i.e., the thermal resistance from junction to case. Were it possible to obtain thermal resistance of zero from junction to air (infinite heat sink, and a thermally perfect transistor), an infinite amount of power could be dissipated in the transistor up to ambient temperature of $T_{J_{max}}$ as long as the circuit thermal stability criterion is satisfied.

It is important to design a power amplifier that will satisfy both the limitation imposed by the maximum junction temperature and the circuit thermal-stability criterion. Unless the signal consists of repeated square wave signals that may cause the maximum possible dissipation in the transistors, it is usually sufficient to design the power amplifier for sine-wave operation. Since the thermal time constant of the power transistor (typical values are 70 to 120 milliseconds) is usually greater than the period of the signal, square wave signals which occasionally do occur will tend to be averaged out and result in an average power dissipation lower than the peak dissipation caused by the square wave. When audio power amplifiers are designed using the above criteria, they are quite stable thermally, since speech and music waves usually produce a low average dissipation. If, however, it is desired to amplify sine wave signals, the power amplifier will still operate safely over the ambient temperature range for which it was designed.

Since maximum dissipation, for class A operation, occurs at quiescent operation, the power amplifier should be designed so that the circuit satisfies both the circuit thermal-stability criterion and the limitation of maximum junction temperature, under *quiescent operation*, up to the highest ambient temperature required. If the circuit meets these requirements under quiescent conditions, both the junction temperature and stability requirements will be satisfied under any signal conditions. Therefore, if a class-A amplifier is stable under idling conditions, the circuit thermal stability will improve when a signal output is obtained, and the junction temperature will be lowered because transistor dissipation will be reduced. This applies to both signal-ended and push-pull class-A amplifiers since the conditions of efficiency and power dissipation described are applicable to class-A amplifiers in general.

Actually, in high power audio amplifiers, it is usually more desirable to operate the output stage class B. For safe, stable operation of high-power class B amplifiers (under sine wave conditions), the circuit should be designed so that both the maximum junction-temperature requirement and circuit thermal-stability criterion are satisfied, at 40% of the maximum power output, up to the highest ambient temperature required. This will ensure stability of the amplifier under any power output conditions. *Testing the amplifier for stability at the extremes of conditions (no power output) and at maximum power output is not sufficient, since, between these conditions, there exists a power output which may cause the amplifier* *to be unstable.* Even when speech and music are applied to the amplifier, it is quite possible that the average level would be of such a value as to cause more dissipation in the output transistors than would occur at maximum power output. (Refer to Fig. 1(B).) However, when the circuit is designed to operate safely at 40% of maximum output, a safety factor is applied, and operation with speech and music results in a conservative amplifier design.

Referring again to Fig. 16, the upper set of curves (1A, 2A, and 3A) might illustrate a level of internal transistor dissipation which would correspond to the maximum dissipation encountered in the amplifier. The lower set of curves (1, 2, and 3) might illustrate the condition of minimum transistor dissipation (quiescent operation for class B). Then, at a given ambient temperature, the transistor dissipation would vary between $P_1$ and $P_2$; and the amplifier should be designed so that the thermal-stability criterion is satisfied at all times.

It may be seen from Fig. 16 that, when additional power is dissipated in the transistor for a given circuit, the maximum safe ambient temperature must be reduced to satisfy the requirements of maximum junction temperature and/or the circuit thermal-stability criterion. *It may therefore be stated that, for a given circuit, the safe allowable transistor power dissipation may be exchanged for higher ambient temperature operation, and vice-versa.*

The importance of stabilization and/or compensation is further demonstrated by Fig. 16 where it may be seen that, for the uncompensated circuit (Curve 3A) operating at a high transistor dissipation, the circuit is unstable at $T_3$ because the thermal-stability criterion is not satisfied. By adding compensation and/or stabilization, a circuit is obtained which results in Curve 2A. This circuit is now stable to an ambient temperature between $T_4$ and $T_5$. If the circuit were perfectly stabilized, Curve 1A would result, and the amplifier would operate to ambient temperature $T_5$. The limitation at this point would be the maximum junction temperature. The difference between $T_5$ and $T_6$ would be the ambient temperature exchange required to operate the amplifier at a given maximum power output, corresponding to a dissipation of $P_2$, rather than at some lower output which might correspond to a dissipation of $P_1$.

It is interesting at this point in the discussion to consider the amount of available power that is lost to the transistor and circuit because the transistor is a temperature-sensitive device. If the transistor were uneffected by temperature, the plot of internal power generation versus junction temperature would be a straight horizontal line (zero slope). However, since the basic mechanism of transistor action is dependent on thermal energy, the transistor is necessarily temperature-dependent and, as a result, the plot of internal power generation will increase with junction temperature. Through compensation and/or stabilization, it is possible to "flatten out" this curve, but only at the cost of added circuit complexity, and both d-c and a-c power loss.

In stabilizing a circuit, the technique usually results in d-c (and sometimes a-c) power loss in the stabilizing network. When compensating a circuit, in addition to the d-c power lost in the compensation network, the added cost of the compensating elements and additional circuit complexity must be taken into consideration. It is therefore up to the designer to decide what sacrifice he is willing to make (in terms of the compensation and/or stabilization required) to operate at a higher power dissipation and/or ambient temperature. Therefore, the question of whether the maximum junction temperature or the circuit thermal stability should set the upper safe ambient temperature will depend on the particular application involved. It may be pointed out that compensation and/or stabilization may often be exchanged for a more efficient heat sink (or vice-versa) depending on whether the designer allows the maximum junction temperature (and power dissipation) to limit the circuit, or the circuit thermal stability to be the limiting factor. Here again, a compromise is required since the size of the heat sink increases rapidly in order to keep its thermal resistance low.

*Practical Example*
*(Considerations for 45-Watt Series Amplifier)*

An example of the graphical presentation of thermal stability, described in the preceding pages, is presented below for the 45-watt series type amplifier previously described. Fig. 17 presents plots of one output transistor quiescent power dissipation versus junction temperature for several conditions of compensation and/or stabilization. Also plotted in Fig. 17 is the approximate maximum thermal resistance from junction to air for the transistor and its cooling media. (The transistors employed in the output stage had a thermal resistance of about 1.3°C/watt).

Curve 1 is a plot of the temperature characteristics of the amplifier with no compensation or stabilization in the circuit; i.e., no thermistors and no emitter resistors in the output stage. If the thermal conductance line is translated to the right until it is tangent to Curve 1, the intersection of this line with the X-axis occurs at about 36°C. Therefore, at an ambient temperature of 36°C, the amplifier will just be stable since $dP_D/dT_J = 1/\theta_T$. Operation of the amplifier using this circuit would consequently be limited (for the idling condition) to ambient temperatures of less than 36°C.

Curve 2 illustrates the effect of adding a 0.5-ohm resistor in the emitter leads of the output transistors (with no other compensation). These resistors tend to "flatten out" or linearize the original curve, as a result of the negative current feedback produced by these resistors, and thereby extend the maximum stable ambient temperature to about 44°C. Since the resistors cannot be capacitively bypassed, the results is a loss of available a-c power output. (For the case of maximum power output, about 5 watts of power is lost in these resistors.)

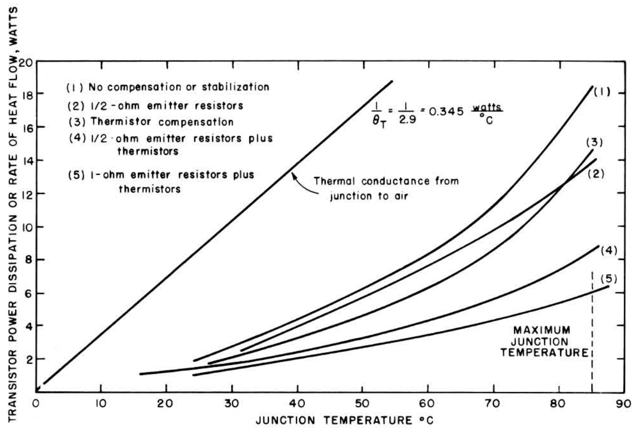


Fig. 17 - Effect of stabilization and/or compensation on the thermal stability of the 45-watt series amplifier.

Curve 3 illustrates the effect of adding only temperature compensation to the circuit in the form of thermistors. The resultant curve is translated down from Curve 1 and appears to have about the same slope. The amplifier will now be stable to an ambient temperature of about 45.5°C. The junction temperature for this condition (where $dP_D/dT_J = 1/\theta_T$) is about 70°C, which is much less than the maximum allowable junction temperature of 85°C.

Curve 4 is a plot of the amplifier circuit with the combination of stabilization (0.5-ohm emitter resistors) and compensation (thermistors). This corresponds to the to the actual circuitry for the 45-watt series amplifier. The combination of stabilization and compensation materially lowers the dissipation curve and also tends to linearize it, resulting in a more stable circuit. By translating the thermal conductance line, it may be seen that the maximum stable ambient temperature for the amplifier is about 60°C, which corresponds to a junction temperature of about 85°C. Quiescent operation of the 45 watt series amplifier is thereby limited to an ambient temperature of less than 60°C.

Curve 5 illustrates the amplifier performance when 1-ohm resistors are placed in the emitters of the output transistors, and also with thermistor compensation. The transistor dissipation curve is further lowered and becomes even more linear. Now the maximum safe ambient temperature is about 65°C. As in the previous case the maximum ambient temperature will be limited by the allowable maximum junction temperature and not the thermal stability.

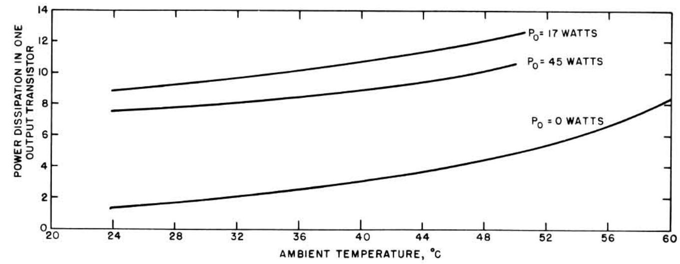


Fig. 18 - Power dissipation for 45-watt series amplifier.

In Fig. 18, transistor dissipation is plotted against ambient temperature for various power outputs. The maximum dissipation for the amplifier occurs at about 17 watts output. The curves of dissipation produced by the a-c signal are roughly parallel to the curve shown for the quiescent operation. Therefore, it is relatively simple to predict the transistor dissipation (with a-c signal power) at higher ambient temperatures by first obtaining the curve for quiescent dissipation versus ambient temperature and then measuring the room-temperature dissipation for a given signal output.

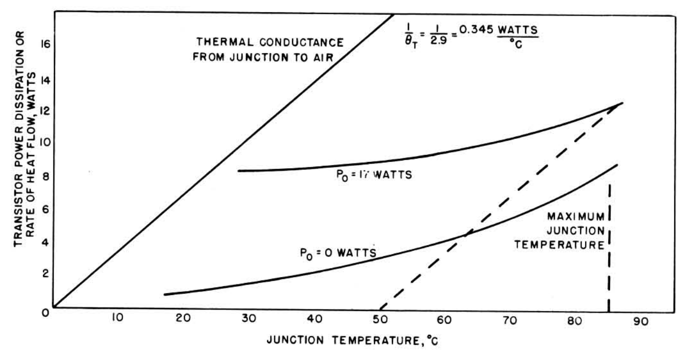


Fig. 19 - Thermal stability of 45-watt series amplifier.

Fig. 19 presents information that allows the designer to determine the maximum power output and the maximum safe ambient temperature for operation of the amplifier. The transistor dissipation for 17 watts output power (approximately the worst condition for dissipation) is plotted as a function of junction temperature. The idling dissipation ($P_o$ = 0 watts) for the amplifier is also replotted on the same graph. It may be seen that the two curves are no longer parallel when plotted against junction temperature. The maximum ambient temperature, for 17 watts output, may now be seen to be about 50°C, where the maximum junction temperature is the limitation. The amplifier will therefore be stable for any power output (maximum of 45 watts) up to 50°C since this temperature was arrived at by considering the worst possible case of transistor dissipation for a sine-wave signal. With speech or music, the amplifier will run well below this dissipation.

Once again, it should be pointed out that the designer must decide what sacrifice he is willing to make for stable higher-power and/or high-temperature operation. In order to design a stable 45-watt amplifier, three thermistors and an additional voltage supply were required. Additionally, about 5 watts of signal lower had to be sacrificed in the emitter resistors to obtain safe operation up to 50°C. Furthermore, a relatively large cooling area was required to obtain high values of thermal conductance from junction to air. For another application, this degree of stability might not be required and the result would be a somewhat simpler circuit and/or a much smaller chassis.