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AC TEMPERATURE COMPENSATION OF INTEGRATED AMPLIFIERS

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UNITED STATES ARMY
ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY

FORT MONMOUTH, N.J.

U. S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT LABORATORY
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AC TEMPERATURE COMPENSATION OF INTEGRATED AMPLIFIERS

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ABSTRACT

An analytical basis for temperature compensation of the AC performance of transistor small-signal amplifiers is not generally available at the present time. This report describes a simple yet accurate design theory in which this compensation is analytically determined by imposing the requirement of equality for the values of the individual small-signal fourpole parameters of the amplifier at its operating temperature limits. For $-30^{\circ}C \leq T \leq 100^{\circ}C$ in a typical noncompensated circuit, power gain, input impedance and output impedance vary by 99%, 71%, and 22%, respectively, while the comparable compensated circuit variation of each of these quantities is less than 9%. In an integrated circuit a single tapped resistance, properly selected, is the only temperature sensitive element required for this compensation.

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CONTENTS

TABLES

FIGURES

AC TEMPERATURE COMPENSATION OF INTEGRATED AMPLIFIERS

INTRODUCTION

One of the more troublesome characteristics of a transistor is its rather pronounced sensitivity to temperature.[1,2] Consequently, in the design of a transistor circuit it is necessary to provide diligently for changes in device parameters due to both self-heating effects and ambient variations. Of primary importance is the stabilization of the DC operating point.[3,4] In addition, it is often necessary to obtain temperature stable AC performance in a transistor circuit. In the case of small-signal amplifiers, an analytical basis for AC temperature compensation is not generally available at the present time.[5] This report describes a fairly simple yet accurate design theory whereby the temperature variations in the transistor small-signal parameters are effectively compensated by a minimum of passive elements. The result is an integrated amplifier whose current gain, voltage gain, power gain, input impedance, and output impedance are virtually insensitive to temperature. The amplifier is termed integrated since the required compensation may best be accomplished first, by analyzing the circuit as an entity, and second, by mounting all components on or within a common substrate.

DESIGN THEORY

The purpose of this section is to provide a design theory for AC temperature compensation of transistor small-signal amplifiers. The first element in this theory is the predictable stabilization of the DC operating point, I_C and V_{CE}, of the transistor by means of temperature sensitive resistors. This subject has been suitably treated in recent articles[3,4,6] and will not be discussed in detail here. However, since it is inextricably connected with the present theory for AC compensation, appropriate mention of it will be made when necessary.

Basically, in this report the AC compensation of a transistor amplifier is determined by matching the values of the individual small-signal fourpole "H" parameters of the circuit[7] at its operating temperature limits. From this, the temperature variations of the circuit resistors required to balance transistor parameter temperature variations are calculated. In addition to its temperature behavior, the quality of an amplifier design is determined by the extent to which it concurrently provides the large AC power gain and the small DC power dissipation desirable in integrated circuits.

The amplifier circuit considered here is shown in Figure 1. Regarding the transistor as specified, this circuit has five resistors (R_E, R_e, R_2, R_3 and R_C), one voltage supply (V_{CC}) and six temperature factors (γ_E, γ_e, γ_2, γ_3, γ_C and γ_V) which are available to satisfy both DC and AC design constraints. (Figure 1 effectively defines the above circuit quantities.) By anticipating the lower and upper operating temperature limits of the circuit (T_y and T_x respectively) and selecting the corresponding transistor DC operating points (I_{Cy}, V_{CEy} and I_{Cx}, V_{CEx} respectively), the essential transistor DC characteristics (I_{By}, V_{BEy} and I_{Bx}, V_{BEx} respectively) and AC characteristics (h_{11y}, h_{12y}, h_{21y}, h_{22y} and h_{11x}, h_{12x}, h_{21x}, h_{22x} respectively) may be found from measurement. (The present theory assumes the range of amplifier operating frequencies is such that the transistor fourpole parameters remain purely real.) From the DC analysis[3,4,6] four (e.g., V_{CC}, R_2, R_3, and R_C) of the above twelve circuit quantities are specified as shown in the appendix. The remaining quantities are determined primarily from the AC analysis.

Considering Figure 2 and the fourpole equations

$$V_1 = H_{11}i_1 + H_{12}V_2$$

and

$$i_2 = H_{21}i_1 + H_{22}V_2, \tag{1}$$

it is evident that the "H" parameters define the small-signal AC characteristics of the circuit. Consequently, amplifier temperature compensation may be accomplished by suitably restricting the temperature behavior of the H parameters. In this case, the imposed restrictions are

$$H_{11y} = H_{11x}$$

$$H_{21y} = H_{21x} \tag{2}$$

and

$$H_{22y} = H_{22x}\,.$$

The reverse voltage transfer ratio, H_{12}, is not included here since its effect on circuit behavior is negligibly small. Substituting the approximate values for the H parameters from Table 1 gives

$$\frac{(h_{11y}+h_{21y}R_e)R_{23}}{(h_{11y}+h_{21y}R_e)+R_{23}} = \frac{(h_{11x}+h_{21x}\gamma_e R_e)\gamma_{23}R_{23}}{(h_{11x}+h_{21x}\gamma_e R_e)+\gamma_{23}R_{23}} \tag{3}$$

$$\frac{(h_{21y})R_{23}}{(h_{11y}+h_{21y}R_e)+R_{23}} = \frac{(h_{21x})\,\gamma_{23}R_{23}}{(h_{11x}+h_{21x}\gamma_e R_e)+\gamma_{23}R_{23}} \tag{4}$$

and

$$1/R_C = 1/\gamma_C R_C\,. \tag{5}$$

It is found that a most useful solution to (3), (4), and (5) results from equating numerators and denominators. Choosing $\gamma_2 = \gamma_3 = \gamma_{23}$, this gives

$$\gamma_{23} = h_{21y}/h_{21x}\,, \qquad \gamma_e = \gamma_{23}\,\frac{R_{23}-h_{11x}}{\gamma_{23}R_{23}-h_{11y}}\,, \quad (6),\ (7)$$

$$R_e = \frac{\gamma_{23}R_{23}-h_{11y}}{h_{21y}} \quad \text{and} \quad \gamma_C = 1. \quad (8),\ (9)$$

This particular solution to (3), (4), and (5) offers simplicity in analytic approach, realizable component requirements, and relatively small penalties in gain performance to achieve temperature compensation. Other solutions are possible but are inherently more complex analytically and also present additional problems in implementation.

In order to assure $\gamma_e > 0$ and $R_e > 0$, (7) and (8) require

$$R_{23} > h_{11x} \quad \text{and} \quad \gamma_{23}R_{23} > h_{11y}. \tag{10}$$

Equations (6) through (9) specify five additional circuit quantities, giving a total of nine of the original twelve unknowns. The remaining quantities may be chosen as desired within reasonable limits. Normally, $\gamma_V = 1$ and γ_E and R_E are selected to maximize the AC power gain (G_x) and minimize the total power dissipation (P_x) of the circuit (see the appendix for P_x). When these goals conflict, a reasonable compromise results if one maximizes the quotient of the AC power gain and DC power dissipation.

With the H parameters completely specified, the power gain

$$G = \frac{H_{21}^2 R_L}{(1+H_{22}R_L)(H_{11}+\Delta^H R_L)} \simeq \frac{H_{21}^2}{H_{11}} \; \frac{R_L}{(1+R_L/R_C)^2}, \tag{11}$$

the input impedance

$$R_i = \frac{H_{11}+\Delta^H R_L}{1+H_{22}R_L} \simeq H_{11}, \tag{12}$$

and the output impedance

$$R_o = \frac{R_g+H_{11}}{H_{22}R_g+\Delta^H} \simeq R_C \tag{13}$$

of the circuit in Figure 1 may be determined readily. The following section indicates the agreement which has been achieved between this design theory and measured circuit performance.

EXPERIMENTAL RESULTS

The results described in this section are based on the behavior of a typical small-signal diffused base silicon transistor. The temperature range of interest is $T_y = -30^\circ C \leq T \leq 100^\circ C = T_x$. Several typical sets of DC operating points are listed in Table II. The DC and AC data corresponding to Set No. 2 are:

a. DC operating points

$I_{Cy} = 1.4$ ma, $V_{CEy} = 13.0$ v $\qquad$ $I_{Cx} = 2.6$ ma, $V_{CEx} = 7.0$ v.

b. DC characteristics

$I_{By} = 42.3\mu a$, $V_{BEy}=0.74$ v $\qquad$ $I_{Bx} = 31.4\mu a$, $V_{BEx} = 0.5$ v .

c. AC characteristics

$h_{11y}=680$ ohms, $h_{12y}=1.21\times10^{-4}$, $h_{21y}=39.3$, $h_{22y}=2.82\times10^{-5}$ ohms^{-1}

$h_{11x}=1200$ ohms, $h_{12x}=3.2\times10^{-4}$, $h_{21x}=93.2$, $h_{22x}=8.95\times10^{-5}$ ohms^{-1}.

Notice that the transistor AC characteristics change drastically for the temperature range under consideration.

Three separate sets of terminal conditions were investigated. The first condition assumes that the amplifier terminal impedances are image matched by the source and the load (i.e., $R_g = R_i$ and $R_L = R_o$). The second condition assumes that the amplifier is an iterative stage (i.e., $R_g = R_o$, $R_L = R_i$). The third condition assumes that $R_g = 1000$ ohms and that R_C is the total load on the amplifier. In this case proper adjustment must be made in the formula for H_{22} in Table 1 ($1/R_C \rightarrow 0$ here) and in equations (11) and (12) ($R_L \rightarrow R_C$ here) to achieve meaningful results. Since the latter case is most easily checked experimentally, measurements were taken for it.

Figure 3 shows the normalized power gain, $G(T)/G(25^{\circ}C)$, versus temperature for the transistor whose characteristics are given above in both a noncompensated circuit (all γ's=1) and a circuit compensated with thermistors according to the design theory of this report. R_C is taken as the total AC load of the amplifier with $R_g=1000$ ohms. In the noncompensated circuit power gain varies from -45% to +54% of its nominal or 25°C value, while in the thermistor compensated case, the maximum variation is +8% which is well over an order of magnitude improvement. The temperature behavior of current gain and voltage gain in the compensated circuit is quite similar to that of power gain as exhibited in Figure 3.

Figure 4 shows the normalized input impedance, $R_i(T)/R_i(25^{\circ}C)$, versus temperature for the same situation as Figure 3. In the noncompensated case input impedance varies from -29% to +42% of its nominal value, while the thermistor compensated variation is +9%. The improvement in stability here is about eight times.

According to (13), the amplifier output impedance, if R_C is included within the amplifier as it will be in all applications, is approximately equal to R_C and should therefore be temperature stable since $\gamma_C = 1$. If the above amplifier designs are provided with image-matched terminations, the total variation in R_o is 22% for the noncompensated circuit and 9% in the thermistor compensated case. Similar behavior prevails for iterative loading. In both of these typical cases, the addition of R_e providing degenerative AC feedback tends to stabilize R_o.

The actual design and performance of the two circuits compared in Figures 3 and 4 are given below.

Circuit Design

NONCOMPENSATED CIRCUIT	THERMISTOR COMPENSATED CIRCUIT	
$R_E=520\ \Omega$	$R_E=491\ \Omega$	$\gamma_E=0.991$
$R_e=0\ \Omega$	$R_e=195\ \Omega$	$\gamma_e=1.02$
$R_2=40{,}500\ \Omega$	$R_2=22{,}700\ \Omega$	$\gamma_{23}=0.42$
$R_3=235{,}000\ \Omega$	$R_3=155{,}000\ \Omega$	$\gamma_{23}=0.42$
$R_C=4{,}500\ \Omega$	$R_C=4{,}300\ \Omega$	$\gamma_C=1.00$
$V_{CC}=20$ v	$V_{CC}=20$ v	$\gamma_V=1.00$
$P_x=53.6$ MW	$P_x=57$ MW	

Circuit Performance

Calculated, Measured	Calculated, Measured
$A_{ix}=80.2$, 85.4	$A_{ix}=26.4$, 25.9
$A_{vx}=-343$, -310	$A_{vx}=-20.1$, -20.8
$G_x=44.4$ db, 44.0 db	$G_x=27.2$ db, 27.3 db
$R_{ix}=1050\ \Omega$, 1190	$R_{ix}=5690\ \Omega$, $5380\ \Omega$

(From Figure 2, $A_i \equiv i_2/i_1$ and $A_v \equiv V_2/V_1$.) The above circuits are as nearly similar in design as can be achieved considering their inherent differences. P_x, V_{CC} and R_C are virtually equal in value in the two circuits, while $R_1=R_E+R_e$ is approximately equal. An examination of this data reveals three striking features. For both circuits the agreement between calculated and measured performance is very close, which indicates the accuracy of the theory. Second, a comparison of the performances of the two circuits reveals that the essential mechanism of AC compensation is one of suppression of amplifier gain and elevation of input impedance by means of a careful mix of both AC emitter degeneration via R_e and temperature dependent signal shunting via R_2 and R_3. The actual compensation is of course more complex than this simple statement can reveal, and an examination of the appendix and Table II can provide insight. This complexity is exemplified by the fact that in order to achieve in the noncompensated circuit, with only emitter degeneration (R_e), the power gain stability of the thermistor compensated circuit, an $R_e \simeq 4500$ ohms is required. The accompanying power gain magnitude is reduced to approximately 8.5 db. The third notable feature is that the only significant temperature variation required in the compensated circuit is in the resistors R_2 and R_3, which have identical temperature factors. R_E and R_e may be fixed values. In fact, the data recorded for Figures 3 and 4 were taken in a circuit in which only R_2 and R_3 varied with temperature. In an integrated semiconductor circuit for example, the temperature sensitive combination of R_2 and R_3 could be implemented by a single tapped resistive element. From this, it is evident that the cost of AC compensation in terms of additional components is rather nominal. It might be added that, for the several hundred circuit designs computed during this project, 80% to 90% of them - comprising most of the well-designed cases - predicted the γ_E and γ_e temperature factors as essentially unity. An additional point of interest is that the functional nature of the temperature variation of R_2 and R_3 is not extremely critical. Both linear and exponential temperature dependencies produced results similar to those shown for thermistors.

Assuming adequate temperature compensation for a small-signal amplifier as discussed above, additional criteria may be introduced in order to obtain the most desirable combination of performance characteristics for an integrated circuit. Specifically, two additional critical characteristics are DC power dissipation and AC power gain. Figure 5 shows the total circuit DC power dissipation at the upper temperature limit for the compensated circuits whose DC stabilities are listed in Table II. It is evident that P_x depends on both DC stability and the total external emitter DC resistance, as previously reported.[3,4,7] Figure 6 shows the gain for the cases considered in Figure 5. Inspecting the two Figures, it is evident that minimum dissipation and maximum gain cannot be achieved with the same circuit design. A reasonable compromise may be found readily by maximizing the quotient G_x/P_x. Examining this quantity,

$$G_x/P_x = \frac{P_{ox}}{P_{ix}} \; \frac{1}{P_x} = P_{ox}P_{ix}^{-1} P_x^{-1} \qquad (15)$$

where P_{ox} and P_{ix} are the AC output and input powers at 100°C, respectively, indicates that the gain-dissipation quotient equals the DC-to-AC efficiency-input power quotient. A finer breakdown shows that maximizing this quotient calls for a combination of large AC output capability and small AC input and total DC dissipation requirements in the circuit. These attributes are admittedly desirable in an integrated amplifier. However, it is conceivable that the addition of a weighting factor or an exponent to this simple expression (15) may sometimes provide a more appropriate figure of merit.[7] Figure 7 shows G_x/P_x for the circuit designs of Figure 6. Note that the cross mark on curve 2 in Figures 5, 6, and 7 corresponds to the circuit whose performance is described by Figures 3 and 4 above.

CONCLUSIONS

The analytical design of small-signal circuits exhibiting temperature compensated AC power gain, input impedance and output impedance is demonstrated in this report. For practical purposes, small (e.g., less than 10% changes in these quantities may be achieved over large operating temperature ranges (e.g., $-30 \leq T \leq 100°C$) by utilizing the correct blend of degenerative AC feedback resistance (R_e) and temperature sensitive input shunting resistance (R_2 and R_3). The added circuit complexity required for this compensation appears to be nominal. In achieving this degree of compensation, the basic element undergoing compensation (the transistor) may exhibit changes in all its small-signal parameters in excess of 100%. Finally, the design theory is directly useful with minor changes in notation for AC temperature compensation of additional small-signal circuits[7] using any one of the six sets of fourpole network parameters to characterize both the device and the circuit.

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APPENDIX

PART I

Referring to Figure 1, the quantities

$$R_1 \equiv R_E + R_e \qquad \text{at } T_x$$

and

$$\gamma_1 R_1 \equiv \gamma_E R_E + \gamma_e R_e \qquad \text{at } T_y$$

are useful in defining the circuit DC constants

$$a_1 = \gamma_1 I_{Ex} - \gamma_v I_{Ey} \qquad c_1 = \gamma_1 I_{Ex} I_{Cy} - \gamma_C I_{Ey} I_{Cx}$$

$$a_2 = \gamma_C I_{Cx} - \gamma_v I_{Cy} \qquad c_2 = \gamma_1 I_{Ex} I_{By} - \gamma_{23} I_{Ey} I_{Bx}$$

$$a_3 = \gamma_{23} I_{Bx} - \gamma_v I_{By}$$

$$d_1 = V_{BEx} - \gamma_v V_{BEy}$$

$$b_1 = V_{CEx} I_{Cy} - \gamma_C V_{CEy} I_{Cx} \qquad d_2 = V_{CBx} - \gamma_v V_{CBy}$$

$$b_2 = V_{BEx} I_{By} - \gamma_{23} V_{BEy} I_{Bx} \qquad d_3 = V_{CEx} - \gamma_v V_{CEy}$$

where $\gamma_2 = \gamma_3 = \gamma_{23}$.

From the above constants the network parameters are given by

$$V_{CC} = \frac{(c_1 R_1 + b_1)}{-a_2} \qquad R_2 = \frac{(c_1 R_1 + b_1)(a_1 R_1 + d_1)}{(a_2 c_2 - a_3 c_1) R_1 + (a_2 b_2 - a_3 b_1)}$$

$$R_3 = \frac{(c_1 R_1 + b_1)(a_1 R_1 + d_1)}{-a_2 (c_2 R_1 + b_2)} \qquad R_C = \frac{(a_1 R_1 + d_1) + d_2}{-a_2} \; .$$

The limiting values of R_1 for positive DC stabilization network elements are

$$R_1 = -b_1/c_1 \qquad R_1 = -b_2/c_2$$

$$R_1 = -d_1/a_1 \qquad R_1 = -d_3/a_1$$

$$R_1 = -\frac{a_2 b_2 - a_3 b_1}{a_2 c_2 - a_3 c_1} \; .$$

For $R_E > 0$ and $\gamma_E R_E > 0$, it is necessary that

$$R_1 > R_e \qquad \text{and} \qquad \gamma_1 R_1 > \gamma_e R_e \; .$$

The total circuit DC power dissipation at T_x is

$$P_x = \frac{\gamma_v}{\gamma_{23}} \left[V_{CC} \quad \frac{\gamma_{23} I_{Cx} R_3 + \gamma_{23} I_{Ex} R_2 + \gamma_v V_{CC}}{R_2 + R_3} \, . \right]$$

PART II

This part of the appendix gives design equations for three widely used d.c. stabilization networks in which all elements may be temperature sensitive.

In essence, the d.c. design theory for the circuits shown on Fig.1(a) may be summarized as follows: 1) Anticipate the lower and upper operating temperatures, T_y and T_x respectively of the circuit. 2) Select the transistor operating point at T_y (i.e., the values of I_{Cy} and V_{CEy}) and T_x (i.e., the values of I_{Cx} and V_{CEx}). The operating points selected should reflect a reasonable amount of drift over the anticipated temperature range. 3) With the transistor at temperature T_y, measure I_{By} and V_{BEy} for the selected values of I_{Cy} and V_{CEy}. Do likewise at T_x. 4) Write two sets of Kirchhoff equations for the circuit, one at T_y and one at T_x. This yields a set of four simultaneous equations (two for each temperature) containing the transistor currents and voltages, the stabilization network elements (R_1, R_2, R_3, R_C and V_{CC} -- see Fig. 1(a)), and their temperature factors ($\gamma_1, \gamma_{23}, \gamma_C$ and so forth where, e.g., $\gamma_1 = R_1 @ T_x / R_1 @ T_y$). All temperature changes in the stabilization network elements are reflected in these equations via the γ factors. 5) Since the transistor currents and voltages are known from 2) and 3), and the γ factors are assumed known ($\gamma_1 = 1, \gamma_2 = \gamma_3 = \gamma_{23}$ as defined by a.c. requirements, and $\gamma_C = 1$.) the set of equations may be solved in terms of any one of the five stabilization network elements. (The equations are solved in terms of R_1 in this note. See Tables I and II A.) 6) Select a value for R_1 and compute the remaining elements from the results of 5). R_1 as well as the operating points should be selected to provide the minimum circuit dc power dissipation consistent with ac performance requirements (see Reference 7 in text).

Part III a

Table I gives a rather lengthy expression for the exact value of H_{22}.

The exact expression may be simply reduced to a shorter exact form.

$$H_{22} = \frac{1}{R_C} + \frac{h_{22}(R_{23}+R_e) + \Delta^h}{(1+h_{22}R_e)\,\Delta}$$

where $\Delta = h_{11} + \dfrac{(1-h_{12})(1+h_{21})}{(1+h_{22}R_e)} \quad R_e + R_{23}$ as before.

PART III b

A detailed analysis of the temperature behavior of H_{22} and R_o for temperature insensitive designs is made in this portion of the appendix.

An examination of h-parameters shows, typically

$$\gamma_{23} = \frac{h_{21y}}{h_{21x}} = \frac{39.3}{93.2} = .420$$

$$\frac{h_{22y}}{h_{22x}} = \frac{2.82 \times 10^{-5}}{8.95 \times 10^{-5}} = .316$$

indicating that the temperature variations of h_{21} and h_{22} are of similar trend.

Using $H_{22} = \dfrac{1}{R_c} + \dfrac{h_{22}\,(R_{23} + R_e) + \Delta^h}{(1 + h_{22}R_e)\,\Delta}$

where $\Delta = h_{11} + \dfrac{(1-h_{12})\,(1+h_{21})\,R_e + R_{23}}{(1 + h_{22}R_e)}$

or within 1%

$$\Delta = h_{11} + h_{21}R_e + R_{23}\ .$$

This Δ is temperature invariant when R_e and γ_e are chosen in the manner outlined in preceding text $\therefore\ \Delta_y = \Delta_x = K$.

Since $h_{22y}\,R_e \ll 1$ and $h_{22x}\,R_e \ll 1$

$$1 + h_{22y}\,R_e \approx 1 + h_{22x}\gamma_e R_e \approx 1$$

{this approximation holds well within 1% for practical designs.}

Using these changes

$$H_{22y} = \frac{1}{R_c} + \frac{h_{22y}\,(R_{23} + R_e) + \Delta^{hy}}{K}$$

$$H_{22x} = \frac{1}{\gamma_c R_c} + \frac{h_{22x}\,(\gamma_{23}R_{23} + \gamma_e R_e) + \Delta^{hx}}{K}$$

$\dfrac{1}{R_c}$ is the predominant term in H_{22},

$\dfrac{h_{22y}\,(\,R_{23} + R_e\,)}{K}$ is about an order of magnitude smaller, and Δ^h an order smaller still.

The temperature variation of Δ^h is therefore of little consequence. Examination of the above equations indicates that γ_{23} tends to offset the temperature trend of h_{22} and thereby acts as a temperature stabilizing influence upon H_{22}.

If this is true, $H_{22y} = H_{22x}$ when $\gamma_c \approx 1$.

To check this, set $H_{22y} = H_{22x}$

$$\frac{1}{R_c} + \frac{h_{22y}(R_{23} + R_e) + \Delta^{hy}}{K} = \frac{1}{\gamma_c R_c} + \frac{h_{22x}(\gamma_{23}R_{23} + \gamma_e R_e) + \Delta^{hx}}{K}$$

solving for γ_c

$$\gamma_c = \frac{1}{1 + \frac{R_c}{K}\left[h_{22y}(R_{23} + R_e) - h_{22x}(\gamma_{23}R_{23} + \gamma_e R_e) + \Delta^{hy} - \Delta^{hx}\right]} .$$

Using $R_c = 4300\ \Omega$

$(R_{23} + R_e) = 20{,}000\ \Omega$

$(\gamma_{23}R_{23} + \gamma_e R_e) = 8500\ \Omega$

$K = 28{,}200\ \Omega$

$h_{22y} = 2.82 \times 10^{-5}\ \mho$

$h_{22x} = 8.95 \times 10^{-5}\ \mho$

$\Delta^{hy} = 1.4 \times 10^{-2}$

$\Delta^{hx} = 7.7 \times 10^{-2}$

$\gamma_c = 1.04 \approx 1.$

This tells us that we can reasonably assume a temperature insensitive R_c and have H_{22} essentially temperature invariant.

Since $R_o = \dfrac{R_g + H_{11}}{H_{22}R_g + \Delta H}$;

it is obvious that R_o is also temperature invariant since R_g, H_{11}, H_{22}, and ΔH ($\approx H_{11}\ H_{22}$) are essentially constant with temperature.

TABLE I - AC CIRCUIT PARAMETERS

Exact Values

$$H_{11}=\frac{\left[h_{11}+\frac{(1-h_{12})(1+h_{21})}{1+h_{22}R_e}R_e\right]R_{23}}{\Delta}\ ,\quad H_{12}=\frac{\left[h_{12}+\frac{(1-h_{12})h_{22}}{1+h_{22}R_e}R_e\right]R_{23}}{\Delta}\ ,\quad H_{21}=\frac{\left[h_{21}-\frac{(1+h_{21})h_{22}}{1+h_{22}R_e}R_e\right]R_{23}}{\Delta}\ ,$$

$$H_{22}=\frac{\left\{h_{22}+\frac{1}{R_C}-\frac{h_{22}^2}{1+h_{22}R_e}R_e+\frac{1}{R_{23}}\left[(h_{11}+\frac{(1-h_{12})(1+h_{21})}{1+h_{22}R_e}R_e)\frac{1}{R_C}+\frac{\Delta^h+h_{22}R_e}{1+h_{22}R_e}\right]\right\}R_{23}}{\Delta}\ ,$$

$$\Delta=\left[h_{11}+\frac{(1-h_{12})(1+h_{21})}{1+h_{22}R_e}R_e\right]+R_{23} \quad \text{and} \quad R_{23}=\frac{R_2R_3}{R_2R_3}\ .$$

Approximate Values

$$H_{11}\simeq\frac{(h_{11}+h_{21}R_e)R_{23}}{\Delta}\ ,\quad H_{12}\simeq\frac{(h_{12}+h_{22}R_e)R_{23}}{\Delta}\ ,\quad H_{21}\simeq\frac{(h_{21})R_{23}}{\Delta}\ ,\quad H_{22}\simeq 1/R_C\ ,$$

$$\Delta\simeq(h_{11}+h_{21}R_e)+R_{23}\ ,\quad \Delta^H=H_{11}H_{22}-H_{12}H_{21}\simeq H_{11}H_{22}.$$

TABLE II - DC OPERATING POINTS

Identification Number	I_{Cy} (ma)	V_{CEy} (v)	I_{Cx} (ma)	V_{CEx} (v)
1	1.4	14.0	2.6	6.0
2	1.4	13.0	2.6	7.0
3	1.4	12.0	2.6	8.0
4	1.6	14.0	2.4	6.0
5	1.6	13.0	2.4	7.0
6	1.6	12.0	2.4	8.0
7	1.8	13.0	2.2	7.0
8	1.8	12.0	2.2	8.0
9	1.8	11.0	2.2	9.0
10	1.9	10.5	2.1	9.5

TABLE I A

DC Constants

Constants frequently used in the DC design are:

Circuit 1

$a_1 = \gamma_1 I_{Ex} - \gamma_v I_{Ey}$

$a_2 = \gamma_C I_{Cx} - \gamma_v I_{Cy}$

$a_3 = \gamma_{23} I_{Bx} - \gamma_v I_{By}$

$b_1 = V_{CEx} I_{Cy} - \gamma_c V_{CEy} I_{Cx}$

$b_2 = V_{BEx} I_{By} - \gamma_{23} V_{BEy} I_{Bx}$

$c_1 = \gamma_1 I_{Ex} I_{Cy} - \gamma_C I_{Ey} I_{Cx}$

$c_2 = \gamma_1 I_{Ex} I_{By} - \gamma_{23} I_{Ey} I_{Bx}$

$d_1 = V_{BEx} - \gamma_v V_{BEy}$

$d_2 = V_{CBx} - \gamma_v V_{CBy}$

$d_3 = V_{CEx} - \gamma_v V_{CEy}$

Circuit 2

$a_1 = \gamma_1 I_{Ex} - \gamma_v I_{Ey}$

$a_2 = \gamma_C I_{Cx} - \gamma_v I_{Cy}$

$b_1 = V_{CEx} I_{Cy} - \gamma_C V_{CEy} I_{Cx}$

$b_2 = V_{BEx} I_{By} - \gamma_2 V_{BEy} I_{Bx}$

$b_3 = \frac{\gamma_2}{\gamma_3} V_{CBx} I_{Ey} - \gamma_1 V_{CBy} I_{Ex}$

$b_4 = \frac{\gamma_2}{\gamma_3} V_{CBx} I_{By} - \gamma_2 V_{CBy} I_{Bx}$

$b_5 = \frac{\gamma_C}{\gamma_3} V_{CBx} I_{Ey} - \gamma_1 V_{CBy} I_{Ex}$

$c_1 = \gamma_1 I_{Ex} I_{Cy} - \gamma_C I_{Ey} I_{Cx}$

$c_2 = \gamma_1 I_{Ex} I_{By} - \gamma_2 I_{Ey} I_{Bx}$

$d_1 = V_{BEx} - \gamma_v V_{BEy}$

$d_2 = V_{CBx} - \gamma_v V_{CBy}$

$d_3 = V_{CEx} - \gamma_v V_{CEy}$

$d_4 = \frac{\gamma_c}{\gamma_3} V_{CBx} - \gamma_v V_{CBy}$

$e_1 = \frac{\gamma_2}{\gamma_3} V_{CBx} V_{BEy} - V_{CBy} V_{BEx}$

$e_2 = V_{CEx} V_{CBy} - \frac{\gamma_c}{\gamma_3} V_{CEy} V_{CBx}$

Circuit 3

$a_1 = \gamma_1 I_{Ex} - \gamma_v I_{Ey}$

$a_{1B} = \gamma_1 I_{Ex} - \gamma_{vB} I_{Ey}$

$a_2 = \gamma_C I_{Cx} - \gamma_v I_{Cy}$

$a_3 = \gamma_2 I_{Bx} - \gamma_{vB} I_{By}$

$b_1 = V_{CEx} I_{Cy} - \gamma_C V_{CEy} I_{Cx}$

$b_2 = V_{BEx} I_{By} - \gamma_3 V_{BEy} I_{Bx}$

$c_1 = \gamma_1 I_{Ex} I_{Cy} - \gamma_C I_{Ey} I_{Cx}$

$c_2 = \gamma_1 I_{Ex} I_{By} - \gamma_3 I_{Ey} I_{By}$

$d_1 = V_{BEx} - \gamma_{VB} V_{BEy}$

$d_3 = V_{CEx} - \gamma_v V_{CEy}$

The correspondence between stabilization network elements and temperature factors (e.g. γ_1 : R_1 indicates ${}_1 = R_1$ @ T_x/R_1 @ T_y) is:

γ_1 : R_1	γ_1: R_1	γ_1; R_1
γ_{23}: R_2	γ_2: R_2	γ_{VB}: V_{BB}
γ_{23}: R_3	γ_3: R_3	γ_3: R_3
γ_c: R_C	γ_C: R_C	γ_C: R_C
γ_v: V_{CC}	γ_V: V_{CC}	γ_V: V_{CC}

TABLE II A DC DESIGN EQUATIONS

The design equations of most importance for Circuits 1, 2 and 3 are listed below.

The stabilization network parameters are given by:

Circuit 1	Circuit 2	Circuit 3
$V_{CC} = \frac{(c_1R_1+b_1)}{-a_2}$	$V_{CC} = -\frac{(c_1R_1+b_1)(b_3R_1+e_1)+(b_5R_1-e_2)(c_2R_1+b_2)}{a_2(b_3R_1+e_1)-d_4(c_2R_1+b_2)}$	$V_{CC} = \frac{c_1R_1+b_1}{-a_2}$
$R_2 = \frac{(c_1R_1+b_1)(a_1R_1+d_1)}{(a_2c_2-a_3c_1)R_1+(a_2b_2-a_3b_1)}$	$R_2 = -\frac{b_3R_1+e_1}{b_4}$	$V_{BB} = \frac{c_2R_1+b_2}{-a_3}$
$R_3 = \frac{(c_1R_1+b_1)(a_1R_1+d_1)}{-a_2(c_2R_1+b_2)}$	$R_3 = -\frac{b_3R_1+e_1}{c_2R_1+b_2}$	$R_3 = \frac{a_{1B}R_1+d_1}{-a_3}$
$R_C = \frac{(a_1R_1+d_1)+d_2}{-a_2}$	$R_C = -\frac{[(a_1R_1+d_1)+d_2]\,[b_3R_1+e_1]}{a_2(b_3R_1+e_1)-d_4(c_2R_1+b_2)}$	$R_C = \frac{a_1R_1+d_3}{-a_2}$

The limiting value(s) of R_1 for positive stabilization network elements are:

Circuit 1	Circuit 2	Circuit 3
$R_1 = -b_1/c_1$	$R_1 = -e_1/b_3$	$R_1 = -b_1/c_1$
$R_1 = -d_1/a_1$	$R_1 = -b_2/c_2$	$R_1 = -b_2/c_2$
$R_1 = -\frac{a_2b_2-a_3b_1}{a_2c_2-a_3c_1}$	$R_1 = -\frac{d_1+d_2}{a_1}$	$R_1 = -d_1/a_{1B}$
$R_1 = -b_2/c_2$	$R_1 = -\frac{(a_2e_1-b_2d_4)}{(a_2b_3-c_2d_4)}$	$R_1 = -d_3/a_1$
$R_1 = -d_3/a_1$	The zeroes of $AR_1^2 + BR_1 + C = 0$ where $A = c_1b_3+c_2b_5$ $B = (b_1b_3+c_1e_1+b_2b_5-c_2e_2)$ $C = b_1e_1-b_2e_2$	

The total circuit DC power dissipation at the upper temperature is:

Circuit 1	Circuit 2	Circuit 3
$P_x = \frac{\gamma_V}{\gamma_{23}} V_{CC} \left[\frac{\gamma_{23}I_{Cx}R_3+\gamma_{23}I_{Ex}R_2+\gamma_V V_{CC}}{R_2+R_3}\right]$	$P_x = \gamma_V V_{CC}(I_{Cx}+\frac{V_{CBx}}{\gamma_3 R_3})$	$P_x = \gamma_{VB}V_{BB}I_{Bx}+\gamma_V V_{CC}I_{Cx}$

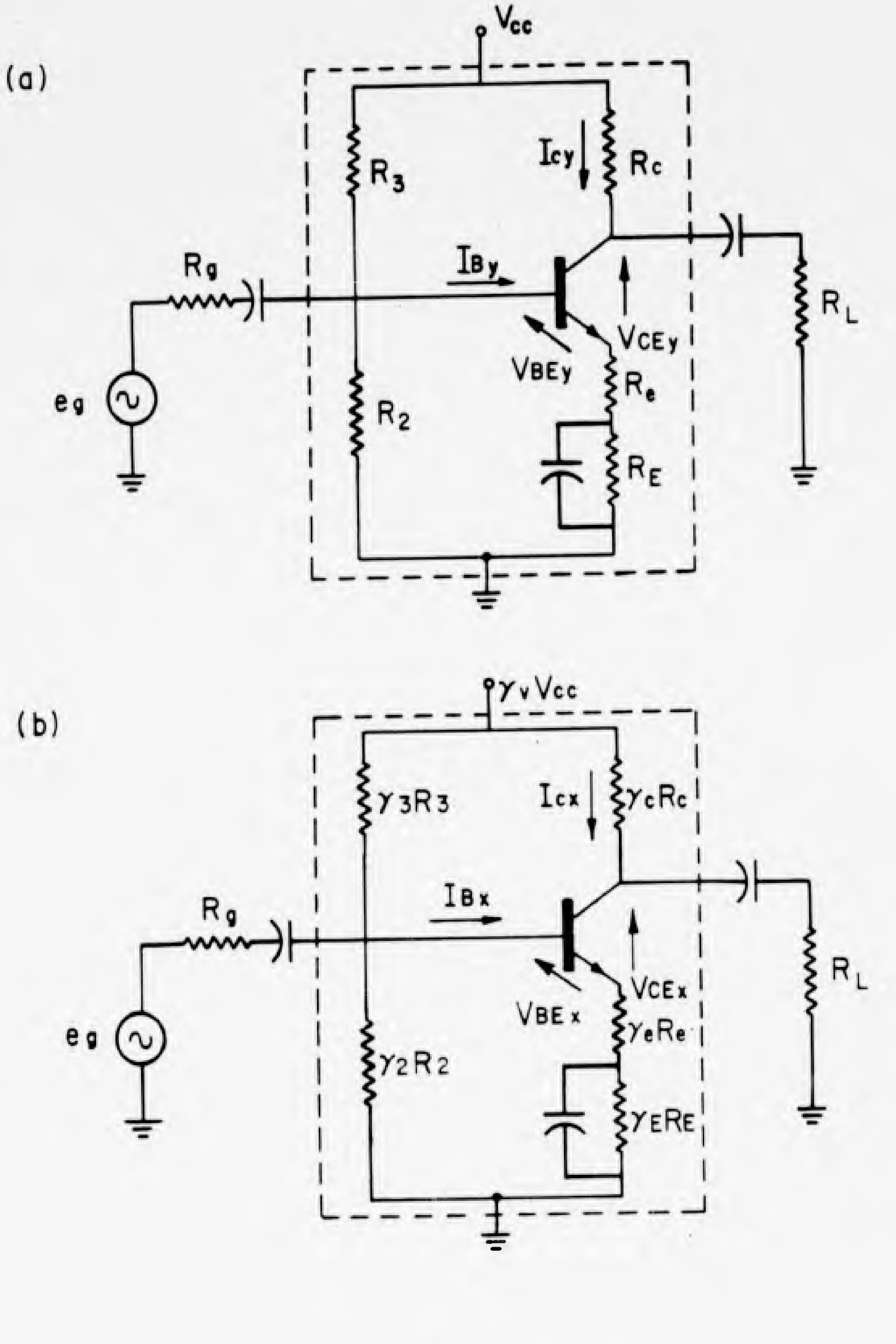
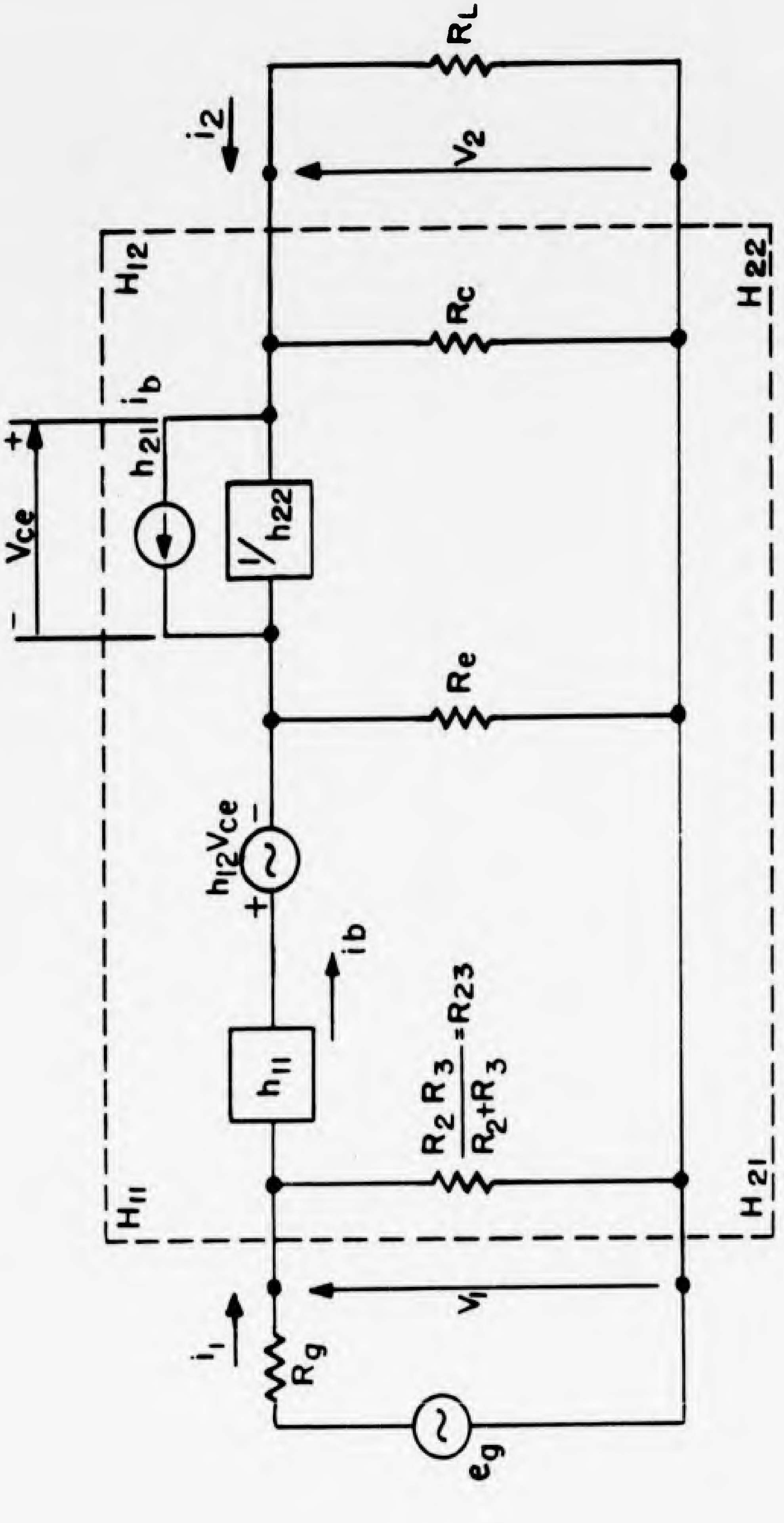


FIG. 1
Circuit Configuration for the Amplifier Stage
(a) Lower Temperature Limit (b) Upper Temperature Limit



An H-Parameter Equivalent Circuit for the Amplifier Stage in Terms of Transistor h-Parameters and Network Resistances

Fig. 2

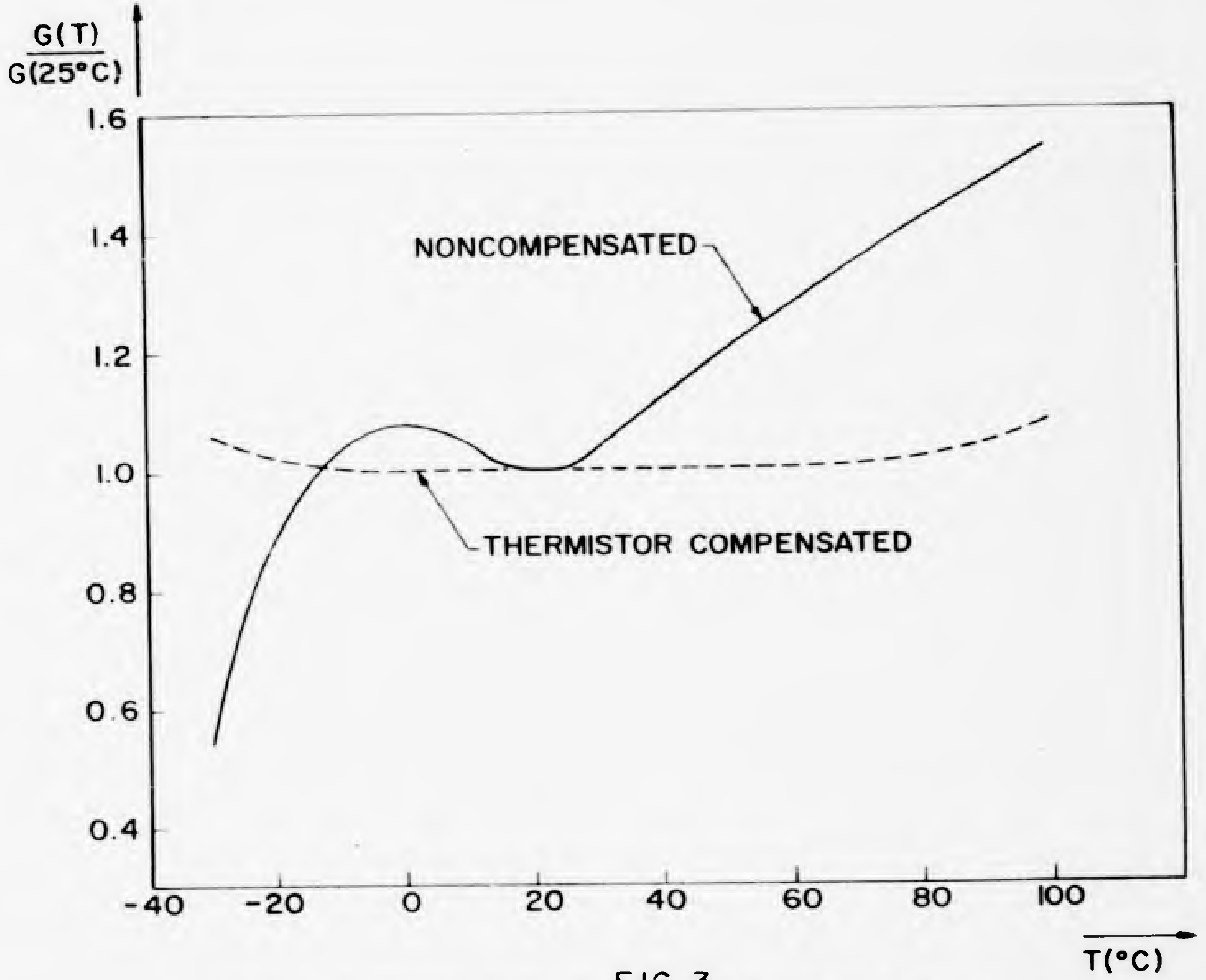


FIG. 3
Curves of Normalized Power Gain vs Temperature for a Thermistor Compensated Design and a Noncompensated Design

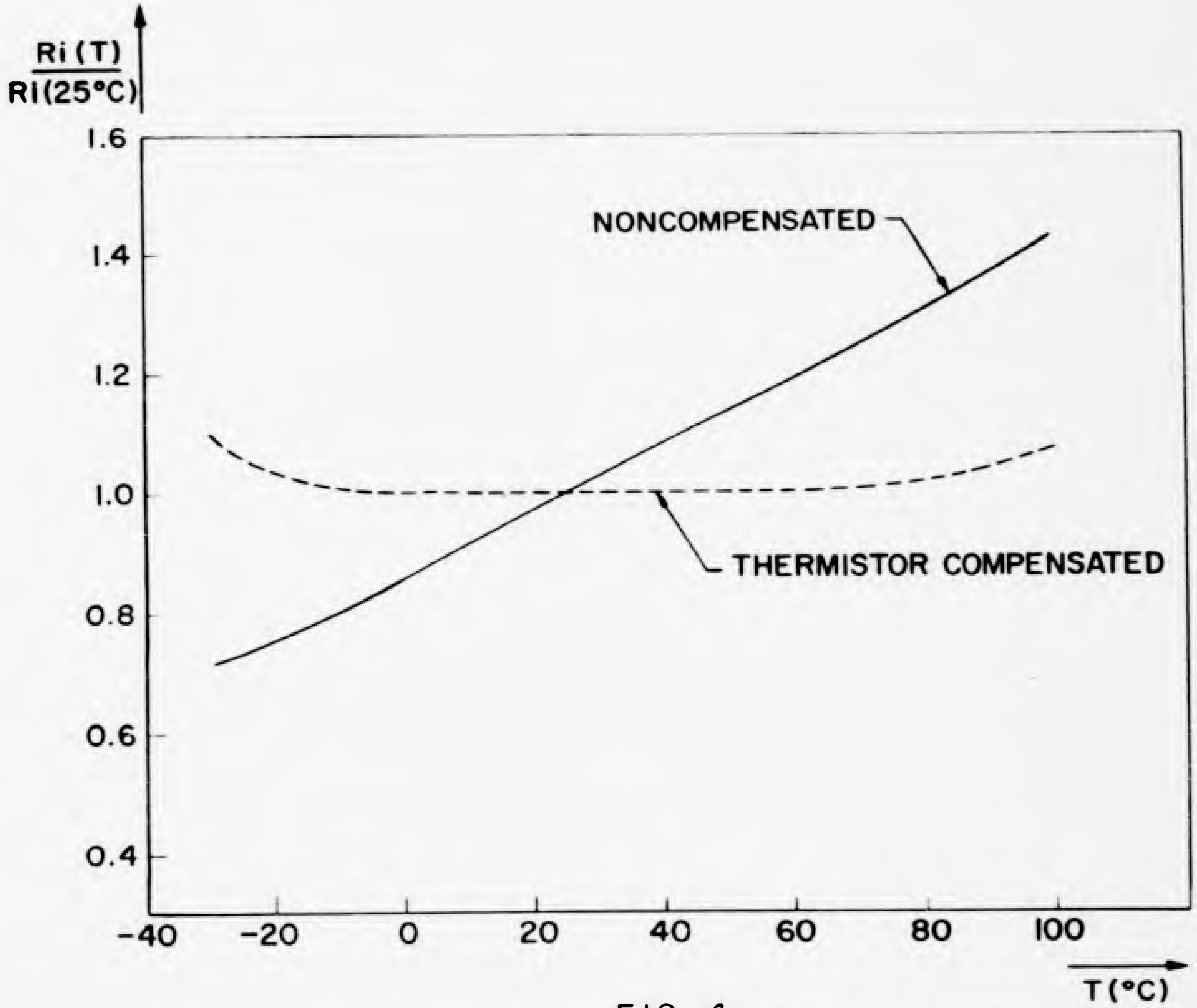
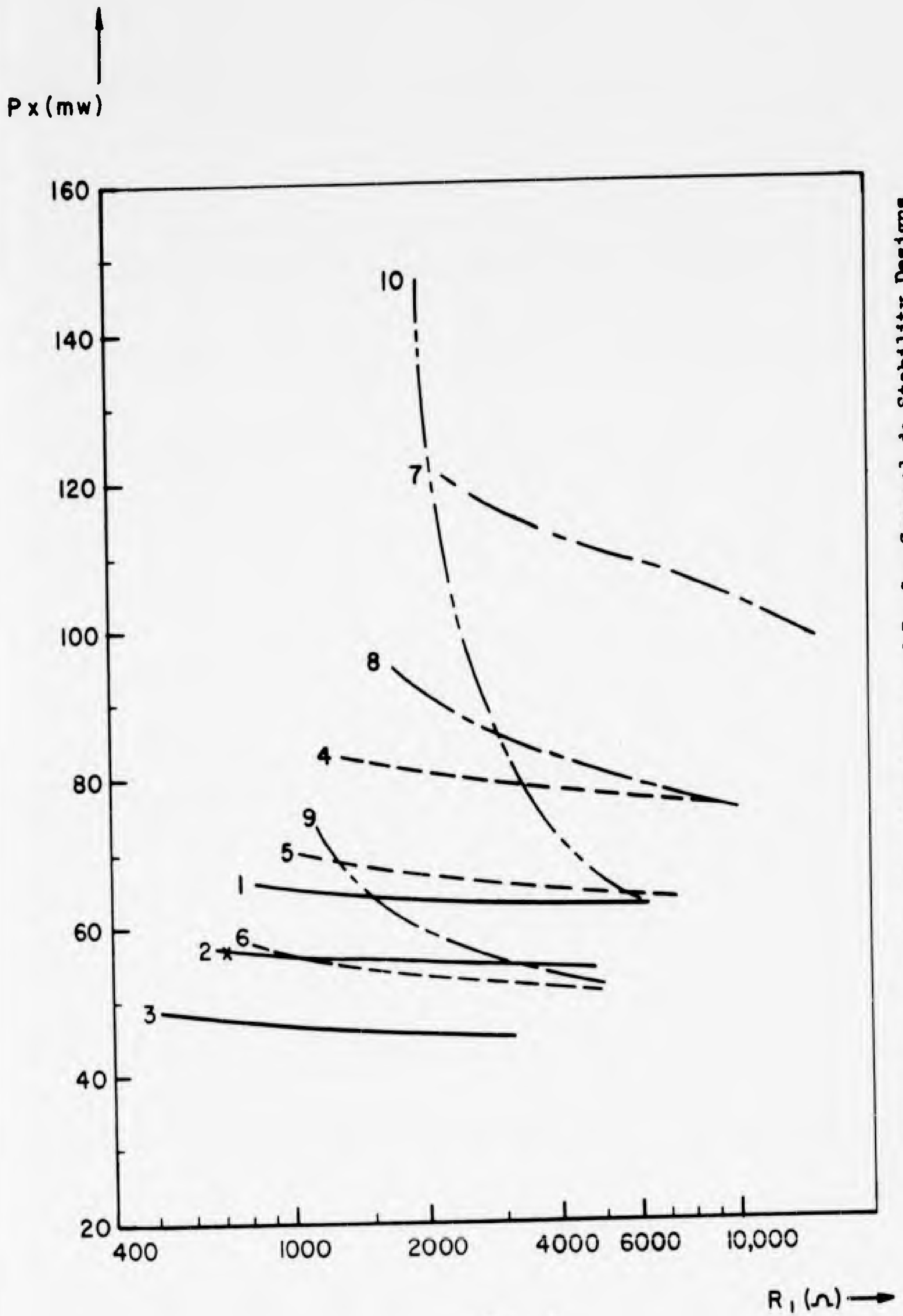


FIG. 4
Curves of Normalized Input Resistance vs Temperature for a Thermistor Compensated Design and a Noncompensated Design



Curves of Power Dissipation vs the Range of R_1 for Several dc Stability Designs

Fig. 5

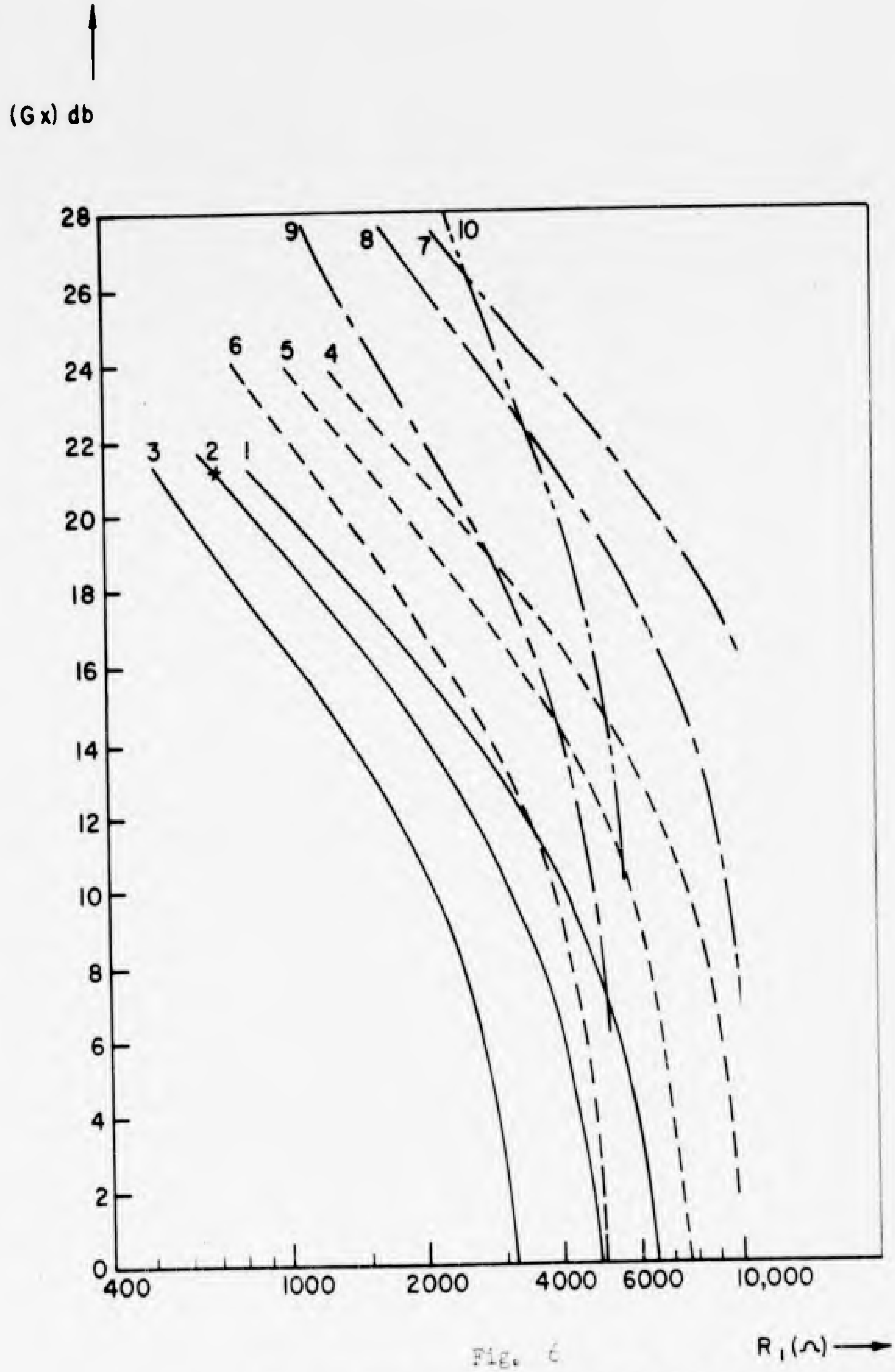


Fig. 6

AC Power Gain vs the Range of R_1 for Several dc Stability Designs

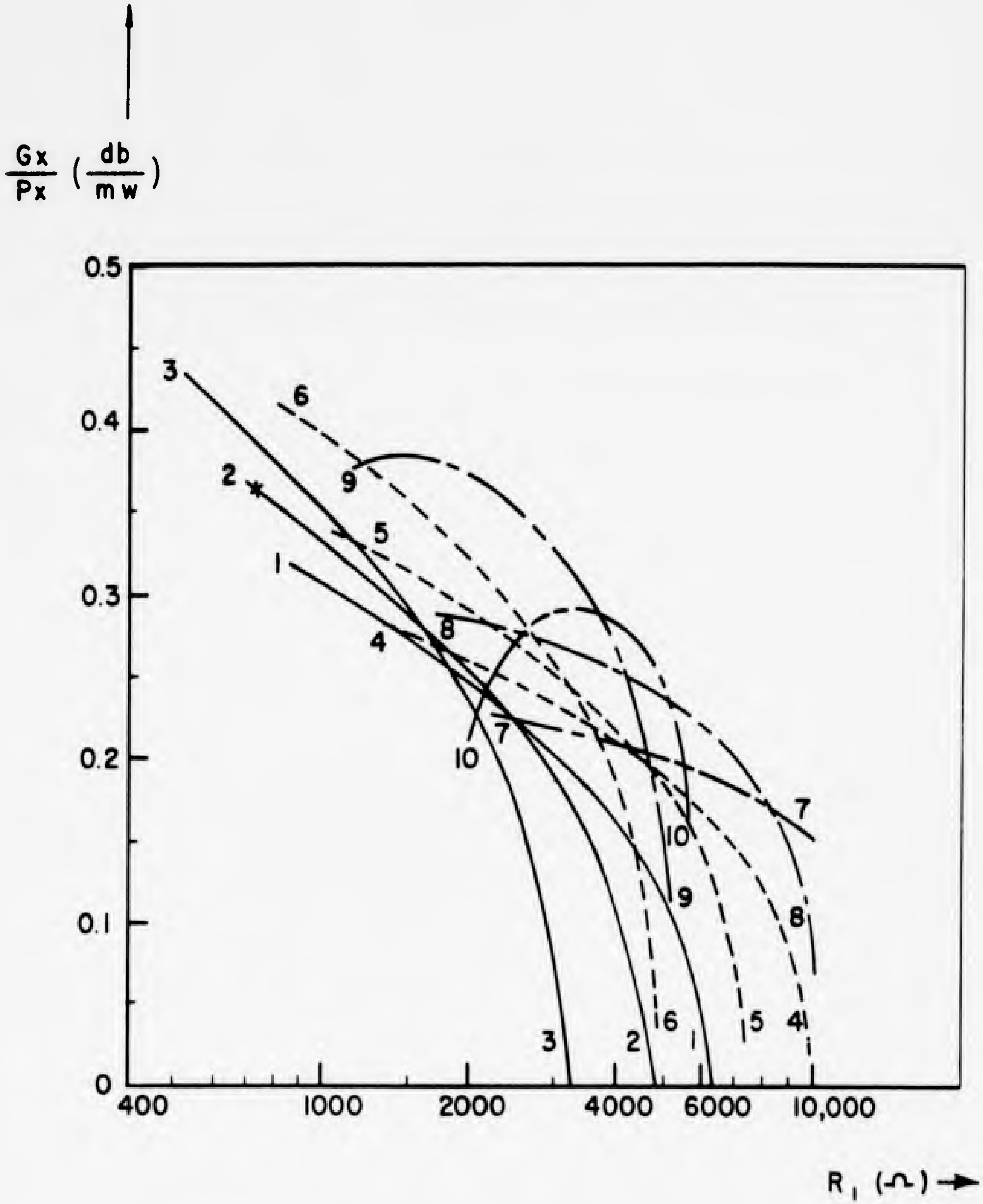
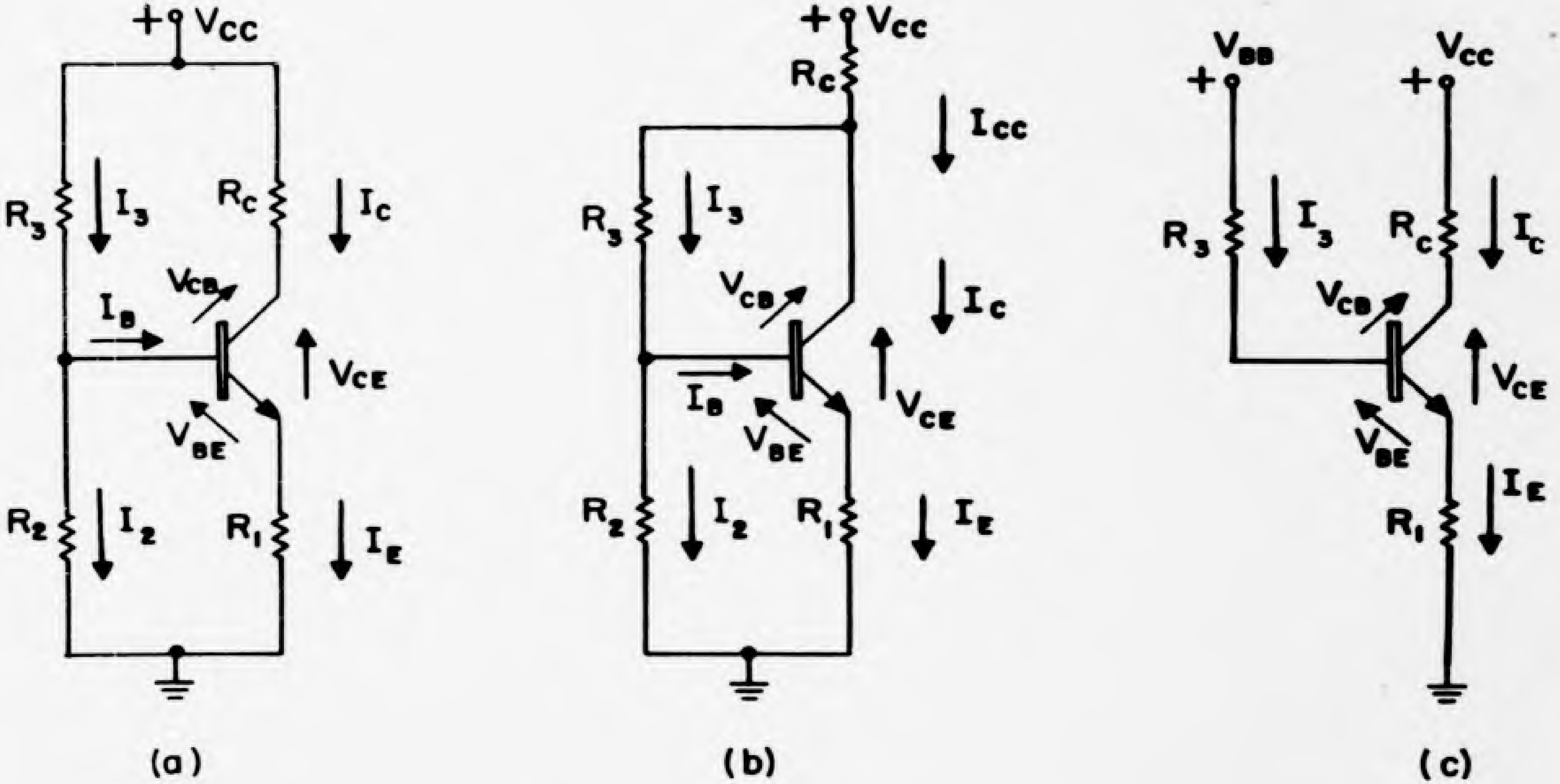


Fig. 7

Figure of Merit vs the Range of R_1 for Several dc Stability Designs

FIG. I A



(a) (b) (c)

DC Design Theory for Circuits

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Unclassified report

An analytical basis for temperature compensation of the AC performance of transistor small-signal amplifiers is not generally available at the present time. This report describes a simple yet accurate design theory in which this compensation is analytically determined by imposing the requirement of equality for the values of the individual small-signal fourpole parameters of the amplifier at its operating temperature limits. For $-30^\circ C \le T \le 100^\circ C$ in a typical noncompensated circuit, power gain, input impedance and output impedance vary by 99%, 71%, and 22%, respectively, while the comparable compensated circuit variation of each of these quantities is less than 9%. In an integrated circuit a single tapped resistance, properly selected, is the only temperature sensitive element required for this compensation.

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2. Transistor Circuits
3. Amplifiers

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Pitzalis, Octavius, Jr.

II. Army Electronics Research and Development Laboratory, Fort Monmouth, N. J.

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