STABILIZATION OF THE OPERATING POINT OF GERMANIUM JUNCTION TRANSISTORS

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In Partial Fulfillment
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Master of Science
in
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by
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PREFACE

The first circuit designers who used transistors in amplifier applications soon found that the operating temperature of the transistor had a profound effect on whether or not the amplifier would perform as intended - or in fact whether it would perform at all.

Certain experimenters turned their attention to the problem of temperature stabilization, notably R. F. Shea, and stability design equations were developed. To date there is little information available on the practical applications of these stability equations; most publications dealing entirely with the theory and leaving the application to the skill of the designer.

The purpose of this investigation was to:

(1) develop the theory of the cause of bias instability and then to develop methods of correcting for the operating point fluctuation using simple linear networks

(2) test the stabilization networks experimentally to determine their effectiveness and to discover what limitations, if any, must be considered in the application of the stability factors

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BY

HUGH ARCHIBALD MacDIARMID

This thesis consists of the theoretical development and experimental testing of a method of stabilization of the quiescent operating point of germanium transistors with change in junction temperature.

The experimental data established the limitations which must be considered in the application of this stabilization method. A guide to the use of Stability Factors in bias stabilization network design is included.

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CHAPTER 1

BIAS AND BIAS STABILIZATION

1.1 Introduction

The purpose of this investigation was to study the problem of bias stabilization in germanium junction transistor amplifier circuits.

1.2 Bias

Most transistor amplifier circuits are designed around a transistor which is biased to operate at a selected quiescent operating point[1] on the V_C - I_C characteristic plane. The transistor is biased by direct-current voltages and currents.

The choice of operating point will depend on the function of the amplifier, however it will usually be selected to give optimum amplifier performance. Any change in the location of the quiescent point will therefore result in an inferior circuit operation.

Careful selection of the operating point is essential for good circuit engineering and the stability of this Q point under dynamic operation of the amplifier is most important.

1.3 Operating Point Instability

The operating point is established by direct-current voltages and currents. Circuit conditions which change the

---

1 - See Appendix B.4

magnitudes of the bias currents and voltages will cause the quiescent point to wander. A shift in operating point position during circuit operation may result in any one (or more) of the following undesirable effects:

(1) non-linear distortion

(2) signal clipping

(3) h parameter variation[2]

(4) thermal runaway[3]

(5) amplifier cut-off

Absolute stability of the operating point is not practicable, therefore the circuit must be designed to tolerate some variation of the quiescent point. This is quite satisfactory (for the circuit designer) providing the movement of the operating point is predictable or, better still, can be constrained to vary within specified limits.

1.4 The Cause of Operating Point Instability

The main reason for operating point instability is that the transistor is very sensitive to change of temperature. Change in junction temperature[4] caused by change in ambient air temperature[5] or by internal heating will result in the operating point shifting from the selected design position.

---

2 - See Appendix B.13
3 - See Appendix C
4 - See Appendix B.6
5 - See Appendix B.5

The bias must be stabilized against changes in junction temperature to prevent this undesired movement if the operating point is to remain reasonably constant.

1. 5 Interchangeability of Transistors

At the present state of transistor production there is considerable variation among transistors of the same type due to the manufacturing tolerances required to prevent an unduly high rejection loss. The parameters of three transistor types that have identical voltage, current and power ratings are listed in Table 1. This table shows the variation in the h parameters permitted by the manufacturer. The three transistor types are actually constructed to the same specifications and then classified by testing the finished product. The principal measurement of the transistor's merit is the value of h_{fe}. The higher h_{fe} transistors have a larger gain (and are more expensive) than the lower h_{fe} transistors. For example the 2N43 ($9.40) costs more than twice as much as the 2N45 ($4.25).

When a transistor must be changed in a circuit the replacement transistor, even though it is of the same type, may not perform satisfactorily because of the wide spread in the characteristics. Although bias stabilization is not directly concerned with interchangeability it is found that certain stabilization techniques make the circuit less sensitive to the

variations among transistors. Thus bias stabilization indirectly yields an additional advantage in that satisfactory amplifier operation is not nearly so dependent upon the choice of replacement transistor.

TABLE 1

SMALL SIGNAL PARAMETERS OF THREE TRANSISTORS

$T_j = 25^{\circ}C$ $V_c = 5$ v $I_c = 1$ ma $f = 270$ cps

Transistor Type	Design Centre	Production Spread Min.	Max.
GE 2N43			
h_{ob}	0.8 μmhos	0.1	1.5
h_{fe}	42	30	66
h_{ib}	29 ohms	25	35
h_{rb}	5×10^{-4}	1	15
GE 2N44			
h_{ob}	0.9 μmhos	0.1	1.5
h_{fe}	25		
h_{ib}	31 ohms	27	38
h_{rb}	4×10^{-4}	1	13
GE 2N45			
h_{ob}	1.1 μmhos	0.1	1.6
h_{fe}	15		
h_{ib}	31 ohms	27	38
h_{rb}	4×10^{-4}	1	10

CHAPTER 2

THE EFFECT OF TEMPERATURE CHANGE ON THE TRANSISTOR

2. 1 Introduction

The qualitative development of the theory of the effect of change in junction temperature on the transistor bias will be presented in this chapter.

2. 2 Transistor Heating

Transistor junction temperature change is mainly the result of:

(1) change in ambient air temperature

(2) internal heating produced by the transistor currents[1]

The particular mode of transistor operation will determine which of the two heat sources is the more important. For small signal operation the transistor bias currents will be small and will cause the junction temperature to rise slightly above the ambient air temperature, usually not more than a few degrees Centigrade.

For example the GE2N43 transistor, rated at 155 milliwatts collector dissipation at 25°C, has a junction temperature rise of 0.5°C per milliwatt of collector dissipation. Transistor

---

1 - See Appendix B.2

operation at the normal small signal operating point of 5 volts and 1 ma will cause a rise in junction temperature of only 2.5°C above the ambient air temperature.

Power transistors must carry larger currents than the small signal transistors because the input signal to the power amplifier stage is much greater than the small signal stage input. The increased collector dissipation caused by the larger bias currents raises the junction temperature well above the ambient air value.

For example if the same GE2N43 is used as a large signal amplifier the normal operating point is 20 volts and 5 ma and the increase in junction temperature will be 50°C higher than the ambient air temperature.

Thus only the anticipated change in ambient air temperature need be considered for small signal operation. For large signal or power transistor operation the internal heating must be considered as well as the ambient air temperature variation.

2. 3 Internal Bias Currents

The internal bias currents flowing in a transistor, at a fixed temperature, are shown in Figure 2.1.

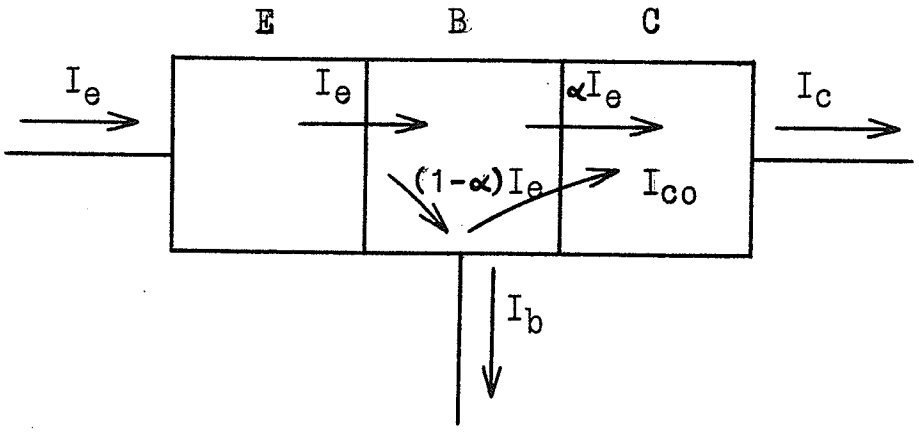

FIGURE 2.1

BIAS CURRENTS IN A PNP TRANSISTOR

The reverse saturation current I_{co}[2] is almost entirely due to the minority carriers[3] in the collector-base region. The minority carriers are holes in the base region and electrons in the collector region. These minority carriers are intrinsic, thermally generated hole-electron pairs and are independent of amounts of impurity atoms added to produce the P-type and N-type regions. At room temperature the value of I_{co} is small compared to the bias currents and depends on the transistor type.[4]

If the junction temperature rises to a higher temperature more hole-electron pairs are generated in the base-collector region. The holes migrate to the collector and the electrons to the base causing the reverse saturation current I_{co} to increase by an amount equal to ΔI_{co}.

---

2 - See Appendix A
3 - R. D. Middlebrook, Junction Transistor Theory, Wiley 1957, P. 25.
4 - See Table 2, Page 11.

The base region is of N-type germanium and has electrons as the majority current carriers. The increase in electrons in the base region, caused by the increase in I_{CO}, produces an electron excess. Some of these excess electrons may flow out of the base lead. The magnitude of this base current will be determined by the base circuit resistance, including the base contact resistance[5].

If only part of the electrons can flow out of the base lead, (in a fixed time), the remaining electrons will create an increase in the majority carrier density in the base region. The increase in base electrons lowers the potential barrier between the emitter and the base thereby permitting more holes to flow from the emitter region. As the base region is relatively narrow some of the holes from the emitter will flow to the collector. The remainder of the holes will recombine with electrons in the base region. The increase in emitter current therefore results in an increased collector current.

The incremental changes in the bias currents are shown in Figure 2.2.

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5 - See Appendix A.2, Figure A.5.

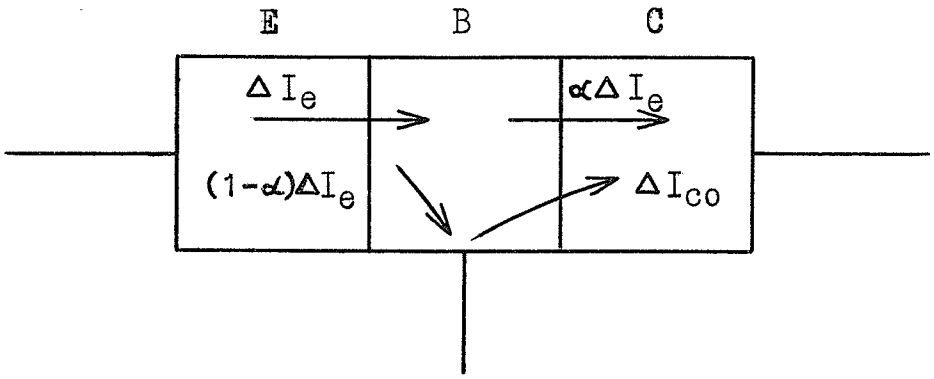

FIGURE 2.2

INCREMENTAL CHANGES IN THE BIAS CURRENTS OF A PNP TRANSISTOR

The increase in collector current causes an increase in junction temperature which generates more hole-electron pairs and causes a further increase in collector current. This cumulative heating effect will continue until one of the following conditions results:

(1) the transistor junction temperature reaches an equilibrium point

(2) the transistor is destroyed by overheating[6]

An increase in junction temperature will therefore produce the following changes:

(1) an increase in the reverse saturation current I_{co}

(2) an increase in emitter current

(3) an increase in collector current

(4) a lower base-emitter diode resistance.

---

6 - See Appendix C.

TABLE 2

VALUE OF I_{co} AT 25°C FOR CERTAIN TRANSISTORS

Transistor Type	I_{co} μa	V_{cb} Volts	Power Rating
2N44	8	45	155 mw
2N68	100	10	2.5 w
2N78	6	15	65 mw
2N170	5	5	25 mw
2N430	0.25	5	150 mw
CK790	50	20	200 mw
H-1	500	30	20 w
H-2	1100	30	20 w
H-3	200	30	5 w
H-4	200	30	5 w

CHAPTER 3

OPERATING POINT STABILIZATION

3. 1 Introduction

The stabilization of the operating point against change in junction temperature is achieved when the collector current is held constant for all junction temperature values in the operating range. This ideal stabilization is not practicable and a compromise must be accepted where the collector current is permitted to increase by a fixed amount which will depend on the stabilization method used.

3. 2 Stabilization Requirements

The collector current variation depends on the following conditions:

(1) the change in emitter current with junction temperature

(2) the change in reverse saturation current with junction temperature

These two conditions may be considered separately. The change in emitter current depends on the change in the emitter-base diode resistance with temperature. As the junction temperature increases the diode resistance decreases linearly. To hold the emitter current constant the emitter-base voltage

must be decreased at a rate of approximately 2.5 millivolts per degree Centigrade[1]. This is equivalent to shifting the common-base input characteristic[2] to the left by 2.5 millivolts per degree Centigrade rise in the junction temperature. The change in emitter-base voltage with temperature may be expressed as:

$$\frac{\Delta V_{eb}}{\Delta T} \cong -0.0025 \text{ volts/}^{o}C \qquad 3.1$$

The change in reverse saturation current depends on the thermal generation of minority carriers with change in junction temperature. I_{co} increases exponentially at a rate of approximately ten percent per degree Centigrade rise in junction temperature. The change in I_{co} may be expressed as[3]:

$$\frac{\Delta I_{co}}{\Delta T} \cong (0.10)\ I_{co} \qquad 3.2$$

The relative change of V_{eb} and I_{co} with junction temperature is shown in Figure 3.1.

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1 - H. C. Lin and A. A. Barco Transistors I, R.C.A. laboratories 1956, P. 372.
2 - See Appendix B.14
3 - See Appendix A.

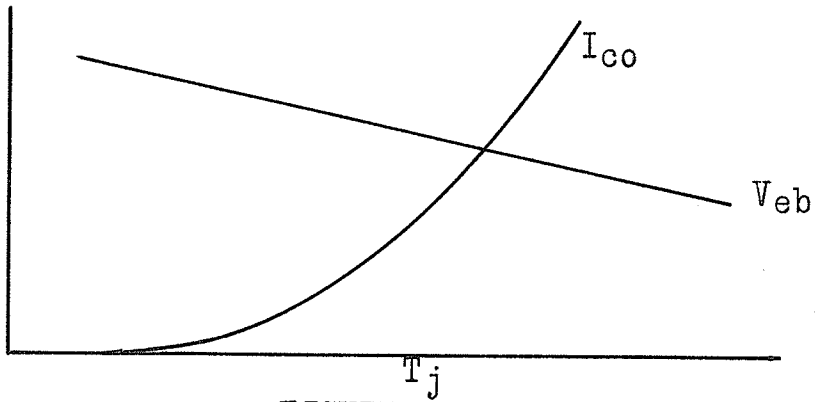

FIGURE 3.1

CHANGE IN V_{eb} AND I_{co} WITH JUNCTION TEMPERATURE

The rate of change in V_{eb} is constant over the operating range. The change in I_{co}, however, is small at low temperatures but becomes very large at higher junction temperatures.

3.3 Stabilization Methods

Low power small signal transistors have a small I_{co} value at room temperature, of the order of a few microamperes[4]. Below room temperature the change in V_{eb} has a greater effect on the change in collector current than the change in I_{co}. Above room temperature the exponential increase in I_{co} soon dominates the effect of change in V_{eb} and the change in collector current may be considered to be due almost entirely to the increase in I_{co}.

The two effects may be considered separately as follows:

(1) a low temperature effect due to change in V_{eb}

(2) a high temperature effect due to change in I_{co}

4 - See Table 2, Page 11.

Stabilization methods must therefore provide a means of compensating for both the linear decrease in V_{eb} and the exponential increase in I_{co}.

3. 4 Stabilization by Degenerative Feedback

Degenerative feedback networks may be used for stabilizing the operating point. These feedback circuits (consisting of linear resistive elements) provide sufficient collector current stabilization for most practical amplifier circuits.

The feedback method compensates for both the low and high temperature effects as follows:

(1) a resistance is inserted in the emitter lead; the voltage drop across this resistance tends to suppress the effect of change in V_{eb}

(2) a feedback network is used to decrease the base current bias to compensate for the increase in I_{co}

These two feedback circuits although intended to counteract separate effects are in fact complementary. The emitter resistance chosen to suppress the change in V_{eb} becomes a part of the feedback network required to compensate for increase in I_{co}.

The degenerative feedback network development will be divided into two parts. The first part will show the effect of emitter resistance; the second part will show how the change in I_{co} is counteracted by a combination of current and voltage feedback.

CHAPTER 4

DEVELOPMENT OF THE STABILIZATION NETWORK

4. 1 Introduction

The common-emitter, single battery bias circuit will be used for the development of the stabilization network for the following reasons:

(1) the common-emitter circuit provides the highest gain; and is used for most amplifier applications

(2) the common-emitter configuration is most severely affected by the increase in I_{co} because of the base injection effect of I_{co} on collector current[1]

(3) the single-battery bias provides the most economical circuit particularly where space and weight limitations must be considered

(4) the common-emitter stabilization networks may be adapted to the common-base or common-collector amplifier circuits by minor changes in the resistance networks and the bias battery location

---

1 - See Appendix A.

(5) the common-emitter single-battery bias circuit represents the most general case as it includes almost all amplifier applications

4. 2 Stabilization for Variation of V_{eb}

The effect of emitter resistance on emitter current variation may be examined by considering the circuit shown in Figure 4.1.

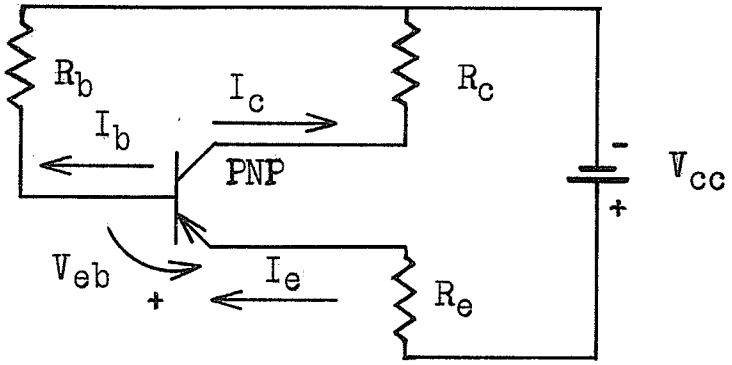

FIGURE 4.1

BIAS CURRENTS IN A TRANSISTOR CIRCUIT

The following equation may be obtained by considering the voltages around the emitter-base circuit:

$$V_{cc} = V_{eb} + I_eR_e + I_bR_b \qquad 4.1$$

The bias currents flowing in the transistor are shown in Figure 4.2.

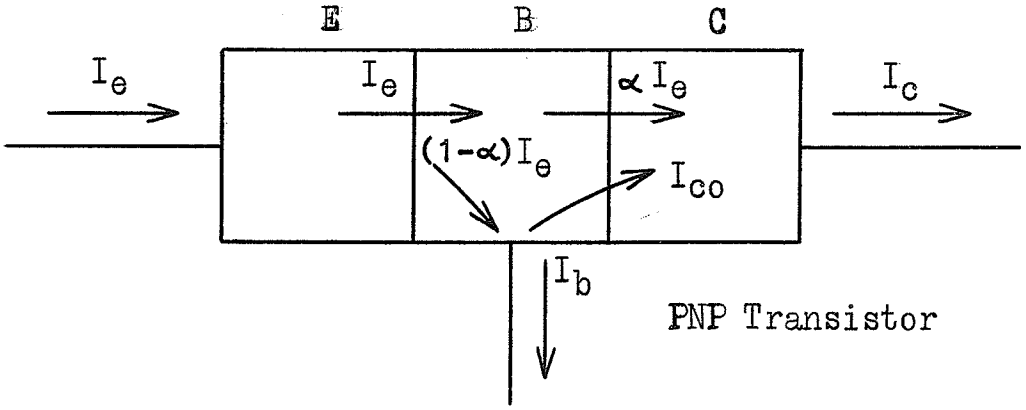

FIGURE 4.2

BIAS CURRENTS IN A TRANSISTOR

The following current equations may be obtained, by inspection, from Figure 4.2:

$$I_e = I_b + I_c \qquad 4.2$$

and $$I_c = \alpha I_e + I_{co} \qquad 4.3$$

If the value of I_e from equation 4.2 is substituted for I_e in equation 4.3 and the resulting equation solved for I_c the following equations will be obtained:

$$I_c = \left[\frac{\alpha}{1-\alpha}\right] I_b + \left[\frac{1}{1-\alpha}\right] I_{co} \qquad 4.4$$

or[2] $$I_c = \beta I_b + \gamma I_{co} \qquad 4.5$$

and $$I_b = \left[\frac{1-\alpha}{\alpha}\right] I_c - \left[\frac{I_{co}}{\alpha}\right] \qquad 4.6$$

If the value of I_b from equation 4.6 is substituted

---

2 - See Appendix B.11 and B.12

for I_b in equation 4.1 then equation 4.1 becomes:

$$V_{cc} = V_{eb} + I_e R - I_{co} R_b \qquad 4.7$$

where $$R = R_e + R_b(1-\alpha) \qquad 4.8$$

As V_{eb} is a non-linear function of emitter current the solution for equation 4.7 may be obtained by graphical construction using the common-base input characteristic curve. The junction temperature is assumed to be constant at room temperature (i.e. 25°C). The graphical solution is shown in Figure 4.3.

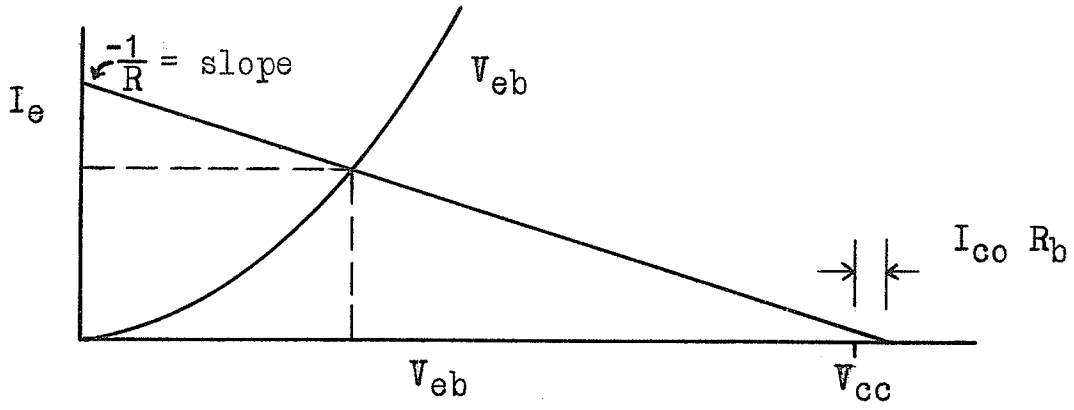

FIGURE 4.3

GRAPHICAL SOLUTION OF EQUATION 4.7

Refer to Figure 4.3. A decrease in junction temperature will cause the V_{eb}-I_e curve to move to the right. The same temperature change will cause an exponential decrease in I_{co}. (Note that I_{co} is relatively small when compared to I_e at room temperature; therefore the decrease in I_{co} will have

a negligible effect on the value of I_e). The decrease in temperature will cause a decrease in I_e.

The effect of a temperature drop on the emitter current is shown in Figure 4.4.

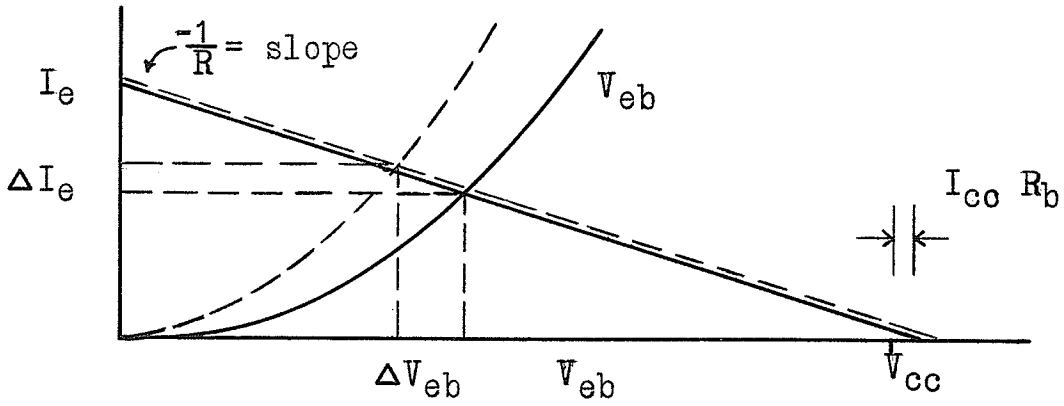

FIGURE 4.4

EFFECT OF TEMPERATURE DECREASE ON EMITTER CURRENT

Refer to Figure 4.3. An increase in junction temperature will cause the V_{eb}-I_e curve to move to the left. The same temperature change will cause a large increase (exponential) in I_{co}.

The large increase in I_{co} will cause the resistance line to rise vertically (without changing slope). The increase in temperature will cause a large increase in I_e.

The effect of a temperature rise on emitter current is shown in Figure 4.5.

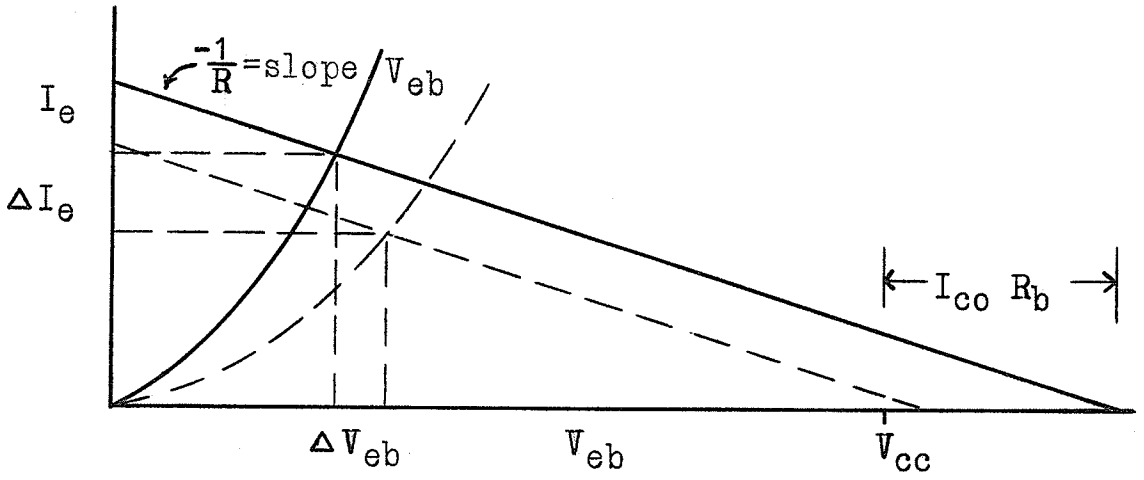

FIGURE 4.5

EFFECT OF TEMPERATURE INCREASE ON EMITTER CURRENT

When I_{co} is relatively small compared to I_e its variation has little effect on the emitter current, however as I_{co} becomes large with respect to I_e its effect on I_e is much more pronounced.

If I_e is held relatively constant with temperature change and I_{co} is negligibly small, the change in I_c will be small. This may be confirmed by considering the current relationship expressed in equation 4.3:

$$I_c = \alpha I_e + I_{co} \qquad 4.3$$

Thus stabilizing the emitter current at low temperatures has the effect of stabilizing the collector current against variation in junction temperature.

The change in I_e with junction temperature change may be minimized by making R large. This value of R is determined by the values of R_e and R_b. The value of R was defined in equation 4.8 as:

$$R = R_e + R_b(1 - \alpha) \qquad 4.8$$

The values of emitter current, collector current and base current are chosen. The value of I_b required to bias the transistor at this operating point determines the value of R_b. The relationship between I_b and R_b may be obtained by rearranging equation 4.1 as follows:

$$R_b = \frac{V_{cc} - V_{eb} - I_eR_e}{I_b} \qquad 4.9$$

If V_{eb} is small compared to V_{cc} (as is normally the case) it may be neglected and equation 4.9 then reduces to:

$$R_b = \frac{V_{cc} - I_eR_e}{I_b} \qquad 4.10$$

As R_b is fixed by the operating point the only means of increasing R is by making R_e larger. Any increase in R_e will require a corresponding increase in V_{cc} if I_b is to remain constant. The relationship between R_e, V_{cc} and I_b may

be obtained by rearranging equation 4.10 as follows:

$$I_b = \frac{V_{cc} - I_e R_e}{R_b} \qquad 4.11$$

The maximum practical value of V_{cc} places an upper limit on the maximum value of R_e. The minimum value of R_e will be determined by the degree of operating point stability required for low temperature operation. Before consideration is given to the method of selecting the value of R_e the effect of the high temperature variation of I_{co} on the operating point will be examined.

4. 3 Stabilization for Variation of I_{co}

The effect of change in I_{co} on collector current may be determined by developing an expression which relates the change in collector current to change in I_{co}. One method consists of setting up the bias network equation in terms of I_c and I_{co} and then taking the derivative of I_c with respect to I_{co}. This derivative may be defined as a stability factor S3 where:

$$S = \frac{dI_c}{dI_{co}} \qquad 4.12$$

The stability factor was originally derived to establish the relationship between the increase in I_{co}, with

3 - See Appendix B.15

junction temperature rise, and the emitter and base lead resistance values required to limit the collector current increase to a specified amount[4].

If the value of I_e obtained from equation 4.3 is substituted for I_e in equation 4.7 and the resulting equation solved for V_{cc} in terms of I_c and I_{co} the following equation is obtained:

$$V_{cc} = V_{eb} + \frac{I_c R}{\alpha} - \frac{I_{co} R}{\alpha} - I_{co} R_b \qquad 4.13$$

Before solving equation 4.13 for I_c the following assumptions are made to simplify the calculations:

(1) V_{eb} is small compared to V_{cc} and may be neglected

(2) Alpha is constant

(3) I_c is independent of V_c

These assumptions are considered to be valid, over the normal operating range, as a first approximation[5]. Their validity will be examined in the experimental portion of this investigation.

If equation 4.13 is solved for I_c, after making the assumptions stated above, the resulting equation is:

---

4 - R. F. Shea Transistor Operation: Stabilization of Operating Points, Proc IRE vol. 40, P. 1435-1437, Nov. 1952.

5 - D. Dewitt and A. Rossoff, Transistor Electronics, McGraw-Hill, 1957, P. 152.

$$I_c = \frac{\alpha V_{cc}}{R} + \frac{R + \alpha R_b}{R} I_{co} \qquad 4.14$$

The derivative of I_c with respect to I_{co} of equation 4.14 is:

$$S = \frac{R + \alpha R_b}{R} \qquad 4.15$$

When the value of R, as defined in equation 4.8, is substituted for R in equation 4.15 the equation for S becomes:

$$S = \frac{R_e + R_b}{R_e + R_b(1-\alpha)} \qquad 4.16$$

Refer to equation 4.12. A low value of S corresponds to a small variation in I_c for a change in I_{co}. A large value of S denotes a much larger increase in I_c for the same I_{co} variation. The boundary values of S may be determined from equation 4.16 by varying R_e from a minimum value (zero) to a maximum value (infinite). R_b cannot be changed because it is fixed by the bias requirement.

When R_e is infinite:

$$S = 1 \qquad 4.17$$

When R_e is zero:

$$S = \frac{1}{1 - \alpha} = \gamma \qquad 4.18$$

Therefore the minimum and maximum values of S are 1 and γ respectively. The actual value of S is a function of R_e as the value of R_b is fixed by the bias.

When S = 1 the change in collector current is limited to the direct change in I_{co} and the stability is good. When $S = \gamma$ the change in collector current is equal to the product γI_{co} and the stability is very poor.

One very serious limitation of this stability network is that any change in R_e required to change S involves a corresponding change in V_{cc}. A more flexible circuit which permits a range of S values for a specified bias and a fixed value of V_{cc} may be obtained by adding a resistance R_a between the base and emitter terminals. The voltage divider network formed by R_a and R_b permits separate control of the bias and the stability. The circuit formed by the addition of R_a is shown in Figure 4.6.

4. 4 Separate Control of Bias and Stabilization

The circuit which permits separate control of the bias and stabilization is shown in Figure 4.6.

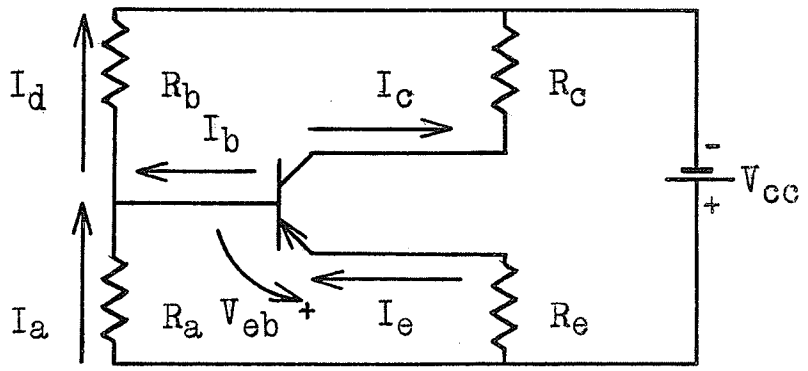

FIGURE 4.6

CIRCUIT FOR SEPARATE BIAS AND STABILITY CONTROL

Refer to Figure 4.6. The following equation may be obtained by considering the voltages around the emitter-base circuit:

$$V_{cc} = V_{eb} + I_d R_b + I_e R_e \qquad 4.19$$

If V_{eb} is negligible the voltage drop across R_a is equal to the drop across R_e and therefore:

$$I_a R_a = I_e R_e \qquad 4.20$$

and

$$I_a = \frac{I_e R_e}{R_a} \qquad 4.21$$

The sum of the currents at the junction of the base and resistances R_a and R_b is:

$$I_d = I_a + I_b \qquad 4.22$$

If the value of I_a from equation 4.21 is substituted for I_a in equation 4.22 the following equation is obtained:

$$I_d = I_b + \frac{I_e R_e}{R_a} \qquad 4.23$$

If the value of I_d from equation 4.23 is substituted for I_d in equation 4.19 and V_{eb} is neglected, equation 4.19 becomes:

$$V_{cc} = I_e R_e + I_b R_b + I_e \frac{R_e R_b}{R_a} \qquad 4.24$$

I_e and I_b may be written in terms of I_c and I_{co} as follows: (See equations 4.3 and 4.6)

$$I_e = \frac{I_c - I_{co}}{\alpha} \qquad 4.25$$

$$I_b = \frac{(1-\alpha)\, I_c - I_{co}}{\alpha} \qquad 4.26$$

If the values of I_e from equation 4.25 and I_b from equation 4.26 are substituted for I_e and I_b, respectively, in equation 4.24 the resulting equation may be written as:

$$\alpha V_{cc} = I_c R' - I_{co} R'' \qquad 4.27$$

where $R' = \frac{R_aR_e + R_aR_b(1-\alpha) + R_bR_e}{R_a}$ 4.28

and $R'' = \frac{R_aR_e + R_aR_b + R_bR_e}{R_a}$ 4.29

If equation 4.27 is solved for I_c the following equation is obtained:

$$I_c = \frac{I_{co}\, R''}{R'} + \frac{\alpha V_{cc}}{R'} \qquad 4.30$$

The derivative of I_c with respect to I_{co} of equation 4.30 is:

$$S = \frac{dI_c}{dI_{co}} = \frac{R''}{R'} \qquad 4.31$$

When the values of R' and R'' as defined in equation 4.28 and equation 4.29, respectively, are substituted for R' and R'' in equation 4.31 the following equation is obtained:

$$S = \frac{R_aR_e + R_aR_b + R_bR_e}{R_aR_e + R_aR_b(1-\alpha) + R_bR_e} \qquad 4.32$$

Equation 4.32 may be written in a simple form by dividing the numerator and the denominator by $\frac{1}{R_aR_b}$, then:

$$S = \frac{1 + \frac{R_e}{R_a} + \frac{R_e}{R_b}}{1-\alpha + \frac{R_e}{R_a} + \frac{R_e}{R_b}} \qquad 4.33$$

An equation for the base current bias (for fixed values of I_e and V_{cc}) may be obtained by rearranging equation 4.24 as follows:

$$I_b = \frac{V_{cc} - I_e R_e \left[\frac{R_a + R_b}{R_a}\right]}{R_b} \qquad 4.34$$

A study of equation 4.33 and equation 4.34 reveals that even if V_{cc}, I_e and I_b are constant it is still possible to vary S by a suitable choice of R_a, R_b and R_e.

A study of Figure 4.6 and equation 4.33 shows that the value of R_e has a great influence on the stability. The current through R_e produces a degenerative feedback voltage across R_e. When R_e is zero the feedback voltage will be zero and the stability is very low.

Another stabilization network using both current and voltage feedback may also be developed[6]. This network has certain disadvantages when compared to the network considered here.

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6 - See Appendix F.

CHAPTER 5

DESIGN OF THE STABILIZATION NETWORK

5.1 Introduction

The method used to design a stabilization network will now be developed. A typical design calculation will also be carried out to illustrate the design principles involved.

The design considerations will be limited to the stabilization network; that is the part of the circuit design required after the following initial design steps have been completed:

(1) the transistor type has been selected to meet the amplifier performance specifications

(2) the operating point has been chosen to suit the signal input and output requirements

(3) the permissible variation in the operating point has been determined

(4) the anticipated maximum and minimum junction temperature values have been determined

As the design steps listed in the previous paragraph are outside the scope of this investigation typical values for each step will be assumed when the exemplary stabilization network is calculated.

5. 2 Stabilization Design Considerations

The following information is necessary for the design of a stabilization network:

(1) the amplifier performance specifications

(2) the transistor performance specifications

The amplifier performance data must include:

(1) V_c and I_c; the values of the operating point

(2) ΔI_c; the permissible operating point variation

(3) ΔT_j; the anticipated change in junction temperature

(4) R_c; the load resistance value

The transistor performance data must include:

(1) the value of alpha at the operating point

(2) the variation of I_{co} with change in T_j

(3) the V_c-I_c characteristic curves

The following quantities may then be calculated from the amplifier and transistor performance data:

(1) ΔI_{co}; the change in I_{co} for ΔT_j

(2) S; the required stability factor

(3) V_{cc}; the battery voltage

(4) R_a, R_b and R_e; the stabilization network resistance values

5. 3 The Stabilization Network Resistances

The bias network shown in Figure 5.1 will be used for the stabilization network calculations. This network is identical with the one derived in Chapter 4 and shown in Figure 4.6.

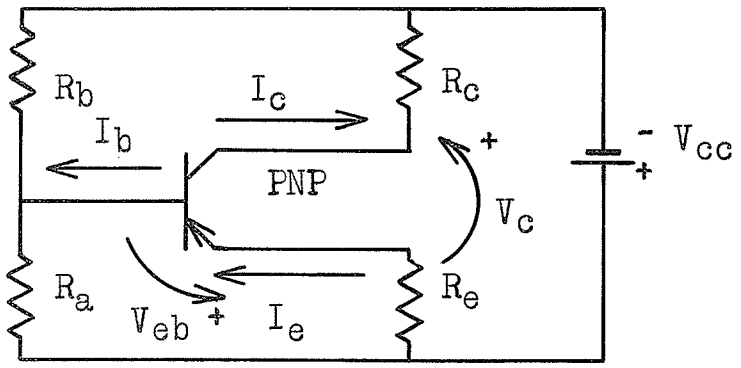

FIGURE 5.1

SINGLE-BATTERY BIAS NETWORK

Refer to Figure 5.1. The values of the three resistances (R_a, R_b and R_e) that form the bias and stabilization network are interdependent, for fixed values of R and S.

The value of R_e must be selected first and it must have a certain minimum resistance. The voltage drop across R_e must be large enough to nullify the variations in V_{eb} with temperature change. A number of R_e values will be used in the stabilization network calculations to show its influence on both the operating point and stability.

When the value of R_e has been selected the values of R_a and R_b may be calculated using the following equations derived in Chapter 4:

(Eq. 4.28) $$R' = \frac{R_aR_e + R_bR_e + R_aR_b(1-\alpha)}{R_a} \qquad 5.1$$

(Eq. 4.29) $$R'' = \frac{R_aR_e + R_bR_e + R_aR_b}{R_a} \qquad 5.2$$

(Eq. 4.30) $$I_c = I_{co}\frac{R''}{R'} + \frac{\alpha V_{cc}}{R'} \qquad 5.3$$

(Eq. 4.31) $$S = \frac{R''}{R'} \qquad 5.4$$

(Eq. 4.32) $$S = \frac{R_aR_e + R_bR_e + R_aR_b}{R_aR_e + R_bR_e + R_aR_b(1-\alpha)} \qquad 5.5$$

Equation 5.3 may be rewritten in the following form by substituting S from equation 5.4 for $\frac{R''}{R'}$:

$$I_c = SI_{co} + \frac{\alpha V_{cc}}{R'} \qquad 5.6$$

The following identity may be shown to exist:

$$\frac{\alpha V_{cc}}{R'} = \frac{V_{cc}(S-1)}{R_b} \qquad 5.7$$

If this value of $\frac{\alpha V_{cc}}{R'}$ from equation 5.7 is substituted in equation 5.6 and the resulting equation solved for

R_b the following equation is obtained:

$$R_b = \frac{V_{cc}\,(S-1)}{(I_c - SI_{co})} \qquad 5.8$$

If equation 5.5 is solved for R_a the following equation is obtained:

$$R_a = \frac{R_b R_e\,(S-1)}{\alpha S R_b - (S-1)(R_b + R_e)} \qquad 5.9$$

The values of R_a and R_b may be calculated from equations 5.9 and 5.8, respectively, after the values of R_e, V_{cc} and S have been determined:

Refer to Figure 5.1. The following equation may be obtained by considering the voltages around the emitter-collector circuit:

$$V_{cc} = I_e R_e + I_c R_c - V_c \qquad 5.10$$

If the value of I_e from equation 4.25 (Page 29) is substituted for I_e in equation 5.10 the following equation is obtained:

$$V_{cc} = \frac{I_c - I_{co}}{\alpha} R_e + I_c R_c - V_c \qquad 5.11$$

If I_{co} is very small compared to I_c (which is normally the case at room temperature) and recalling that alpha is approximately unity, the following approximation may be made:

$$\frac{I_c - I_{co}}{\alpha} \cong I_c \qquad 5.12$$

If I_c is substituted for $\frac{I_c - I_{co}}{\alpha}$ in equation 5.11 the following equation is obtained:

$$V_{cc} = I_c(R_c + R_e) - V_c \qquad 5.13$$

Equation 5.13 may be used to calculate the value of V_{cc}. Note that although the value of R_c influences the value of V_{cc} it has no effect on the stability. The amplifier gain, however, will be affected by the value of R_c. To permit a number of R_e values to be used in the stability network calculations, with a constant voltage V_{cc}, the sum of R_c and R_e was held constant. If $(R_e + R_c)$ is constant, a constant DC load line is obtained. (See Graph 1 , Page 60). The effect of a number of different values of R_c on the amplifier gain was neglected.

5. 4 Calculation of the Stabilization Networks

The following amplifier design conditions were assumed:

(1) transistor type GE 2N44

(2) V_c = 5 volts

(3) I_c = 2 ma

(4) V_{cc} = 10 volts

(5) $(R_c + R_e)$ = 2500 ohms

(6) $\Delta T_j = 40^oC$

(7) T_j varies from 20°C to 60°C

(8) $T_j = 20^oC$ at initial conditions

The following information was obtained from the transistor data supplied by the manufacturer[1]:

(1) I_{co} = 7 μa at 20°C

(2) I_{co} = 90 μa at 60°C

(3) α = 0.955 at the operating point

(4) ΔI_{co} = 83 μa

Stability factors of 3, 6 and 12 were selected. The ΔI_c for each S value is as follows:

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1 - General Electric 2N44 data sheets.

$S = 3$ $\quad \Delta I_C = S \Delta I_{CO} = 0.25$ ma

$S = 6$ $\quad \Delta I_C = S \Delta I_{CO} = 0.50$ ma

$S = 12$ $\quad \Delta I_C = S \Delta I_{CO} = 1.00$ ma

The stabilization network parameters were calculated for each S value using R_e values of:

$R_e = 100$ ohms

$R_e = 250$ ohms

$R_e = 500$ ohms

$R_e = 1000$ ohms

$R_e = 1500$ ohms

The calculated values of R_a and R_b for each S and R_e values are listed on Table 3, Page 40. Each stabilization network on Table 3 was tested in the experimental portion of this investigation.

TABLE 3

THE CALCULATED VALUES OF R_a AND R_b

FOR EACH OF THE SELECTED VALUES OF R_e AND S

S = 12		
R_e - 1500 ohms	R_a - 100000 ohms	R_b - 57500 ohms
R_e - 1000 ohms	R_a - 42000 ohms	R_b - 57500 ohms
R_e - 500 ohms	R_a - 15800 ohms	R_b - 57500 ohms
R_e - 250 ohms	R_a - 6900 ohms	R_b - 57500 ohms
R_e - 100 ohms	R_a - 2640 ohms	R_b - 57500 ohms
S = 6		
R_e - 1500 ohms	R_a - 16600 ohms	R_b - 25500 ohms
R_e - 1000 ohms	R_a - 9120 ohms	R_b - 25500 ohms
R_e - 500 ohms	R_a - 3870 ohms	R_b - 25500 ohms
R_e - 250 ohms	R_a - 1800 ohms	R_b - 25500 ohms
R_e - 100 ohms	R_a - 690 ohms	R_b - 25500 ohms
S = 3		
R_e - 1500 ohms	R_a - 5310 ohms	R_b - 10100 ohms
R_e - 1000 ohms	R_a - 3020 ohms	R_b - 10100 ohms
R_e - 500 ohms	R_a - 1310 ohms	R_b - 10100 ohms
R_e - 250 ohms	R_a - 615 ohms	R_b - 10100 ohms
R_e - 100 ohms	R_a - 238 ohms	R_b - 10100 ohms

CHAPTER 6

EXPERIMENTAL EVALUATION OF THE STABILIZATION NETWORK

6.1 Introduction

The experimental portion of this investigation was performed to:

(1) test the transistors used to obtain characteristic curve data

(2) measure the value of certain transistor parameters

(3) determine the effect of different values of R_e on the stabilization network performance

(4) evaluate the effectiveness of the stability factor, S, in predicting the change in collector current with change in junction temperature

(5) examine the general usefulness of the stabilization network

The special experimental techniques used in this work are described in Appendix F.

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6. 2 Transistor Test Results

Six General Electric 2N44 PNP germanium alloy junction transistors were used for the main experimental work of this investigation.

The six transistors were tested to obtain sufficient data to compare their individual characteristics. The test data for all transistors compared favorably with the average data provided by the manufacturer; all transistors (one was defective) were well within the permissible production deviation for this transistor type, (See Table 1 , Page 5). The data for just one transistor (the one considered to be the most representative of the group) was used to avoid including a large amount of similar information in this report.

The following data was obtained from the transistor tests:

(1) Common-emitter Static Collector Characteristics,
(See Graph 1 , Page 60
and Table 4 , Page 76).

(2) Variation of I_{co} with Collector Voltage
(See Graph 2 , Page 61
and Table 5 , Page 77).

(3) Variation of I_{co} with Junction Temperature
(See Graph 3 , Page 62
and Table 6 , Page 78, linear I_{co} scale).

(See Graph 4, Page 63
and Table 6, Page 78, logarithmic I_{CO} scale).

(4) Common-base Input Characteristic
(See Graph 5, Page 64
and Table 7, Page 79).

(5) Variation of Alpha and Beta with Junction Temperature
(See Graph 6, Page 65
and Table 8, Page 80).

As all curves are similar to the average 2N44 characteristic values, provided by the manufacturer, no discussion of the experimental results is necessary.

6.3 Stabilization Network Test Results

The data obtained from the tests of each stabilization network calculated in Chapter 5 (See Table 3, Page 40), is listed on the following tables:

Table 9, Page 81; R_e = 1500 ohms, S = 3, 6 and 12
Table 10, Page 82; R_e = 1000 ohms, S = 3, 6 and 12
Table 11, Page 83; R_e = 500 ohms, S = 3, 6 and 12
Table 12, Page 84; R_e = 250 ohms, S = 3, 6 and 12
Table 13, Page 85; R_e = 100 ohms, S = 3, 6 and 12

The calculated (using the S value) and experimentally determined change in I_C, with change in T_j, is shown on Table 14, Page 86.

The curves showing the experimentally determined change in I_C, with change in T_j, for each value of S (and all values of R_e used) are shown on the following graphs.

Graph 7	Page 66	S = 12
Graph 8	Page 67	S = 6
Graph 9	Page 68	S = 3

6.4 Discussion of the I_C-T_j Curves

Refer to Graph 7, Page 66, S = 12. The variation in I_C with change in T_j is similar for all values of R_e. The following important points should be noted:

(1) as the value of R_e decreases the I_C - T_j curves become successively lower; and also diverge as the junction temperature value drops.

(2) the actual value of I_C is larger than the value of I_C predicted by the stability factor S. (See Table 14, Page 86).

(3) as the value of R_e decreases, the value of the quiescent point at the initial temperature (20°C) becomes successively lower

Refer to Graph 8, Page 67, S = 6. Once more the variation in I_C with change in T_j is similar for all values of R_e. The important points noted for the S = 12 curves also apply to the S = 6 curves with the additional observation that as the

value of R_e decreases the S = 6 curves diverge more than the S = 12 curves as the junction temperature value drops.

Refer to Graph 9, Page 68, S = 3. Again the variation in I_C with change in T_j is similar for all values of R_e. The important points noted for the S = 12 curves also apply to the S = 3 curves with the added observation that the S = 3 curves diverge more than both the S = 12 and S = 6 curves as the junction temperature decreases.

Refer to Graph 10, Page 69. The curves of S = 3, 6 and 12 for R_e = 1500 ohms show that the values of I_C for junction temperatures below 20°C are approximately the same for all values of S. As the junction temperature increases the value of I_C also increases; the rise in I_C being smaller for the lower values of S. This graph shows that for the highest R_e value used the low temperature variation in I_C is similar for all values of S, however, the variation in I_C is dependent on the S value in the high temperature region above 20°C.

The following graphs show the actual values of I_C obtained experimentally compared with the calculated values of I_C predicted by the S value:

Graph 11, Page 70, R_e = 1500 ohms, S = 12

Graph 12, Page 71, R_e = 1500 ohms, S = 6

Graph 13, Page 72, R_e = 1500 ohms, S = 3

The calculated value of I_c is higher than the experimental value in the low temperature region, however, the predicted value of I_c is less than the experimental value in the high temperature region. The dividing point between the low and high temperature regions is 25°C to 30°C depending on the S value; this changeover point will depend on the transistor type and the initial value of the operating point.

The following conclusions may be drawn from the foregoing observations:

(1) the S value has little influence on the low temperature stability

(2) the S value improves the high temperature stability but the increase in I_c is greater than the predicted amount

(3) the initial operating point value (at 20°C) becomes lower as the value of R_e is decreased. This drop in quiescent point is greater for the lower values of S

(4) the smaller values of R_e (for a particular S value) reduce the low temperature stability slightly

6. 5 Effect of the R_e Value on Stabilization

The effect of the value of R_e on the stabilization may be examined by considering equation 4.24 (Chapter 4).[1]

$$(\text{Eq. } 4.24) \quad V_{cc} = I_bR_b + I_eR_e\left[\frac{R_a + R_b}{R_a}\right] \qquad 6.1$$

The R_e value is modified by the voltage divider network composed of R_a and R_b. Equation 6.1 may be rewritten as:

$$V_{cc} = I_bR_b + I_eR \qquad 6.2$$

$$\text{where } R = R_e\left[\frac{R_a + R_b}{R_a}\right] \qquad 6.3$$

The values of I_b and R_b in equation 6.2 are fixed by the initial bias requirement and are independent of the R_e value used. The value of R in equation 6.3 may be calculated for each S value from the data listed on Table 3, Page 40. This value of R must be constant for all R_e values to satisfy equation 6.2 but will vary with the value of S. The values of R for each S value are listed below; note that as the S value decreases, the value of R is increased.

S = 12	R = 2370 ohms
S = 6	R = 3800 ohms
S = 3	R = 4350 ohms

---

1 - Equation 6.1 will have an additional term when V_{eb} is considered. See equation 6.14, Page 54.

In section 4.2 (Chapter 4) it was shown that the stabilization for change in V_{eb} was improved by increasing the value of R, therefore the low temperature stability should be better as the S value is made smaller.

The change in I_e with change in junction temperature may be calculated using equation 3.1 (Chapter 3). (Refer to Graph 15, Page 74 and Table 15, Page 87 also.)

$$(\text{Eq. } 3.1)\ \frac{\Delta V_{eb}}{\Delta T} \cong -0.0025 \text{ volts/}^{\circ}\text{C} \qquad 6.4$$

The change in V_{eb} from 20°C to 0°C will be:

$$\left|V_{eb}\right| \cong 20 \times 0.0025 = 0.05 \text{ volts}$$

The change in I_e for this change in V_{eb} may be calculated for each value of R using the following equation:[2]

$$\frac{\Delta V_{eb}}{\Delta I_e} \cong R \qquad 6.5$$

The change in I_e from 20°C to 0°C was calculated for each value of R using equation 6.5. As the value of I_b is small compared to I_c the change in I_c will be approximately equal to the I_e variation. The results of the calculations are as follows:

S = 12 $\quad \Delta I_e \cong \Delta I_c \cong 0.21$ ma

S = 6 $\quad \Delta I_e \cong \Delta I_c \cong 0.13$ ma

S = 3 $\quad \Delta I_e \cong \Delta I_c \cong 0.11$ ma

---

2 - The change in I_c caused by a change in I_{co} is considered separately. See equation 6.6, Page 50.

Refer to Graph 10, Page 69. The low temperature variation of I_c agrees closely with the calculated change in I_c, due to the change in V_{eb}, as T_j decreases.

Refer to Graph 5, Page 64. The change in I_c will be greater for lower values of I_e as the R value resistance line will intersect the lower, more curved portion of the V_{eb} - I_e characteristic. This is why the low temperature variation of I_c for very small values of R_e (and small values of I_e) is slightly greater than for the higher R_e values even though the value of R is constant. This slight increase in the low temperature variation of I_c caused the divergence of the curves as the junction temperature decreased. (See Graph 7, Page 66, Graph 8, Page 67 and Graph 9, Page 68.)

The high temperature variation in I_c due to change in V_{eb} may be calculated in a similar manner for the change in junction temperature from 20°C to 60°C. These calculations give the following results:

S = 12	$\Delta I_e \cong \Delta I_c \cong 0.42$ ma
S = 6	$\Delta I_e \cong \Delta I_c \cong 0.25$ ma
S = 3	$\Delta I_e \cong \Delta I_c \cong 0.22$ ma

The change in I_c due to the change in V_{eb} was neglected in the development of the S factor. (V_{eb} was considered to be zero). If this change in I_c due to the variation in V_{eb} is added

to the value of I_C predicted by the S value the total change in I_C may be found from the following equation:

$$\Delta I_C = \frac{\Delta V_{eb}}{R} + S\Delta I_{CO} \qquad 6.6$$

The total change in I_C, for the junction temperature change from 20°C to 60°C, calculated using equation 6.6 is as follows:

$S = 12$ $\qquad \Delta I_C \cong 0.42 + 1.00 \cong 1.42$ ma

$S = 6$ $\qquad \Delta I_C \cong 0.25 + 0.50 \cong 0.75$ ma

$S = 3$ $\qquad \Delta I_C \cong 0.22 + 0.25 \cong 0.47$ ma

These values for the total change in I_C agree reasonably well with the experimental values listed in Table 14, Page 86, the agreement is within ten percent of the experimental value in all cases.[3] The change in I_C caused by the change in V_{eb} has a pronounced effect on the total change in I_C even though R_e was made relatively large. A larger value of R would reduce the effect caused by V_{eb} and this increase in R may be obtained by decreasing the S value while using the largest practical value of R_e to keep the quiescent operating point near the design value.

6.6 Effect of Alpha on the Stabilization

In the development of the S factor the value of alpha

3 - For R_e = 1500 ohms.

was assumed to remain constant with change in junction temperature. Alpha was found to increase with junction temperature rise, the change in alpha with change in junction temperature was measured at a constant operating point of V_c = 5 volts and I_c = 2 ma. The values of beta and gamma were calculated from the experimentally determined value of alpha using equation B.6 and equation B.7 (See Appendix B). The values of alpha, beta and gamma are shown in Table 8, Page 80.

Refer to Graph 6, Page 65. The value of alpha increased uniformly with increase in junction temperature, by a very small amount. The effect of alpha on the S value may be examined by considering equation 4.32 (Chapter 4).

$$\text{(Eq. 4.32)} \quad S = \frac{R_aR_e + R_bR_e + R_aR_b}{R_aR_e + R_bR_e + R_aR_b(1-\alpha)} \qquad 6.7$$

As alpha increases the value of S also increases and even though the change in alpha from 20°C to 60°C is very small (approximately 1.2%) it can cause a very large change in the S value, particularly the larger values of S. For example when only the change in alpha due to junction temperature is considered and change in alpha with emitter current is neglected the S values calculated at 60°C are as follows:

$T_j = 20^oC$	$T_j = 60^oC$
S = 12	S = 16
S = 6	S = 6.7
S = 3	S = 3.2

As alpha is a function of I_e as well as T_j the actual values of alpha at each point will differ slightly from the alpha value at a constant operating point. However, the trend in alpha will be towards an increase as each of the parameters I_e and T_j increase. The net result of an increase in alpha will be an increase in the S value, especially for the larger values of S.

6. 7 Effect of V_c on the Stabilization

Refer to Graph 1, Page 60. In the development of the S factor the value of I_c was assumed to be independent of change in V_c. The variation of I_c with V_c will be very small particularly for small values of I_c and small changes in V_c. Therefore the assumption that I_c was independent of V_c will not introduce any significant error in the change in I_c due to change in T_j.

6. 8 Effect of Degenerative Feedback

The effect of the degenerative feedback may be examined by considering equation 4.5 (Chapter 4).

(Eq. 4.5) $I_c = \beta I_b + \gamma I_{co}$ 6.8

The change in beta and gamma caused by change in junction temperature is shown in Table 8 , Page 80. Note that the values of beta and gamma are approximately equal at each value of junction temperature.

When I_b and I_{co} are of the same order of magnitude (as is the case for small signal transistors) the change in I_c caused by an increase in I_{co} is modified by a decrease in I_b caused by degenerative feedback.

Refer to Graph 16, Page 75. The rate of increase in I_{co} with rise in junction temperature is independent of the transistor circuitry. The decrease in I_b with junction temperature increase is dependent on the S value. As the S value is decreased the value of I_b at any value of T_j is also decreased and the rate of the decrease of I_b becomes greater as the S value is made smaller.

6. 9 Effect of the R_e Value on the Bias

Refer to Graph 7, Page 66. As the value of R_e is decreased the operating point value at the initial temperature (20°C) becomes smaller than the design value of I_c = 2 ma. The reason for the decrease in the quiescent value of I_c may be examined by considering equation 4.19 (Chapter 4).

(Eq. 4.19) $V_{cc} = V_{eb} + I_d R_b + I_e R_e$ 6.9

If V_{eb} is not negligible the following equations may be derived in the same way as equation 4.20 and 4.21 (Chapter 4):

$$I_a R_a = I_e R_e + V_{eb} \qquad 6.10$$

and

$$I_a = \frac{I_e R_e + V_{eb}}{R_a} \qquad 6.11$$

The value of I_d given by equation 4.23 (Chapter 4) will now become:

$$I_d = I_b + \frac{I_e R_e + V_{eb}}{R_a} \qquad 6.12$$

If the value of I_d from equation 6.12 is substituted for I_d in equation 6.9 the following equation results:

$$V_{cc} = I_b R_b + (I_e R_e + V_{eb}) \left[\frac{R_a + R_b}{R_a}\right] \qquad 6.13$$

Equation 6.13 may be rewritten as:

$$V_{cc} = I_b R_b + I_e R_e \left[\frac{R_a + R_b}{R_a}\right] + V_{eb} \left[\frac{R_a + R_b}{R_a}\right] \qquad 6.14$$

If equation 6.1 and 6.13 are compared when I_e, R_a, R_b and R_e, are fixed at some value and V_{eb} is not negligible then:

$$(I_eR_e + V_{eb})\left[\frac{R_a + R_b}{R_a}\right] > I_eR_e\left[\frac{R_a + R_b}{R_a}\right] \qquad 6.15$$

As V_{cc} is constant the term I_bR_b will be larger in equation 6.1 than in equation 6.13. As R_b is fixed the value of I_b calculated from equation 6.1 will be larger than the value of I_b calculated from equation 6.13. The difference between these two values of I_b will become smaller as V_{eb} becomes small compared to I_eR_e.

If V_{eb} is not negligible the value of I_b calculated using equation 6.1 will be larger than the actual value of I_b. The lower value of I_b will give a lower quiescent point than desired. Refer to Graph 1 , Page 60.

Refer to Graph 14, Page 73. The influence of the R_e value on the operating point value may be observed from the graph. As R_e decreases in value the operating point drops from the desired design value of 2 ma. The decrease in I_c is fairly uniform down to R_e = 500 ohms and then drops off very rapidly for lower values of R_e.

The effect of the R_e value on the operating point may be checked using equation 6.14. The I_b value calculated using the actual V_{eb} value may be compared to the I_b value

found when V_{eb} is zero. The value of I_c for each value of I_b may be found from the V_c - I_c curves (See Graph 1, Page 60), and this will give the difference between the actual and predicted quiescent point I_c value. The value of V_{eb} may be obtained from the V_{eb} - I_e curve, (See Graph 5, Page 64).

6.10 Design of the Stabilization Network

One of the most important steps in the design of a reliable stabilization network is choosing the R_e value. The following points should always be considered in the stabilization network design:

(1) R_e should always be as large as possible, consistent with a practical value of V_{cc}

(2) R_e should be checked by calculating the error in the operating point value using equation 6.14

(3) the lowest value of S should be used as this increases the value of R (see equation 6.3) which improves the stabilization for change in V_{eb}

(4) the smaller values of S are not affected by change in alpha as much as larger S values

(5) after R_e and S have been selected the total change in I_c should be calculated using equation 6.6 to determine if the desired bias stabilization will be realized

(6) as the value of S is reduced the power consumed in the voltage divider network (R_a and R_b) increases

(7) as the value of S is reduced the signal loss in the voltage divider network (R_a and R_b) increases

6.11 Conclusion

The stabilization network provides an effective control over the change in operating point due to change in junction temperature.

The following points should always be considered for high temperature operation:

(1) the change in I_c due to change in V_{eb} is not negligible even for very large values of R_e

(2) the value of S increases, as T_j increases, due to the increase in alpha

(3) the effect of R_e on the operating point value must always be checked

The design of a stabilization network will always involve a compromise between the amount of stability desired and the loss of battery power and signal current in the stabilization network.

Although the scope of this investigation was limited the general principles evolved are applicable to all germanium transistors.

6.12 In Retrospect

Some other important aspects of the problem of bias stabilization which could be investigated to extend the range of this study are:

(1) calculation and testing of power transistor stabilization networks

(2) testing the stabilization network developed in Appendix F

(3) design and testing of stabilization networks using non-linear elements[3]

(4) design and testing of stabilization networks using temperature sensitive elements[4]

(5) design and testing of stabilization networks using tandem pair transistor combinations[5]

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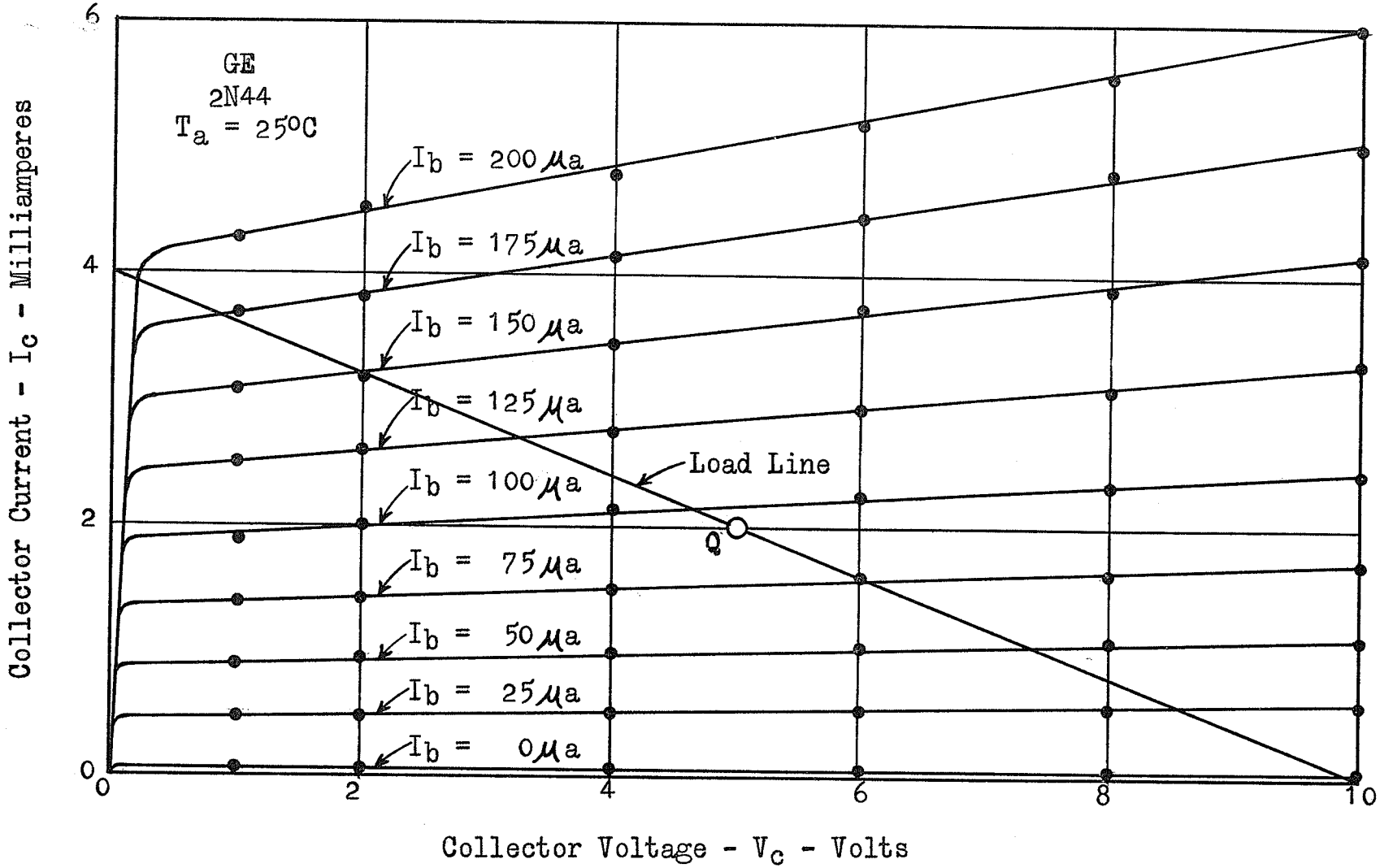
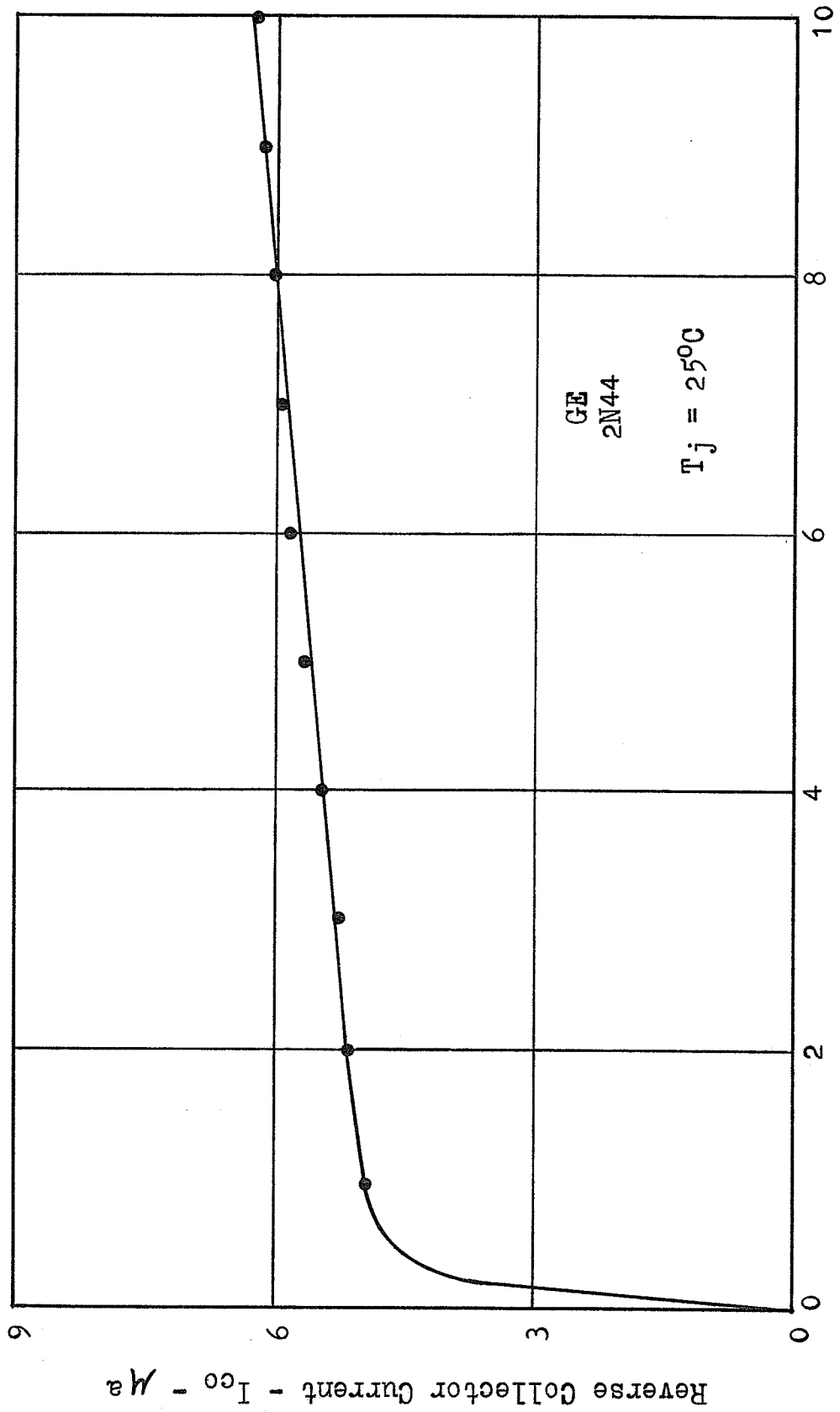
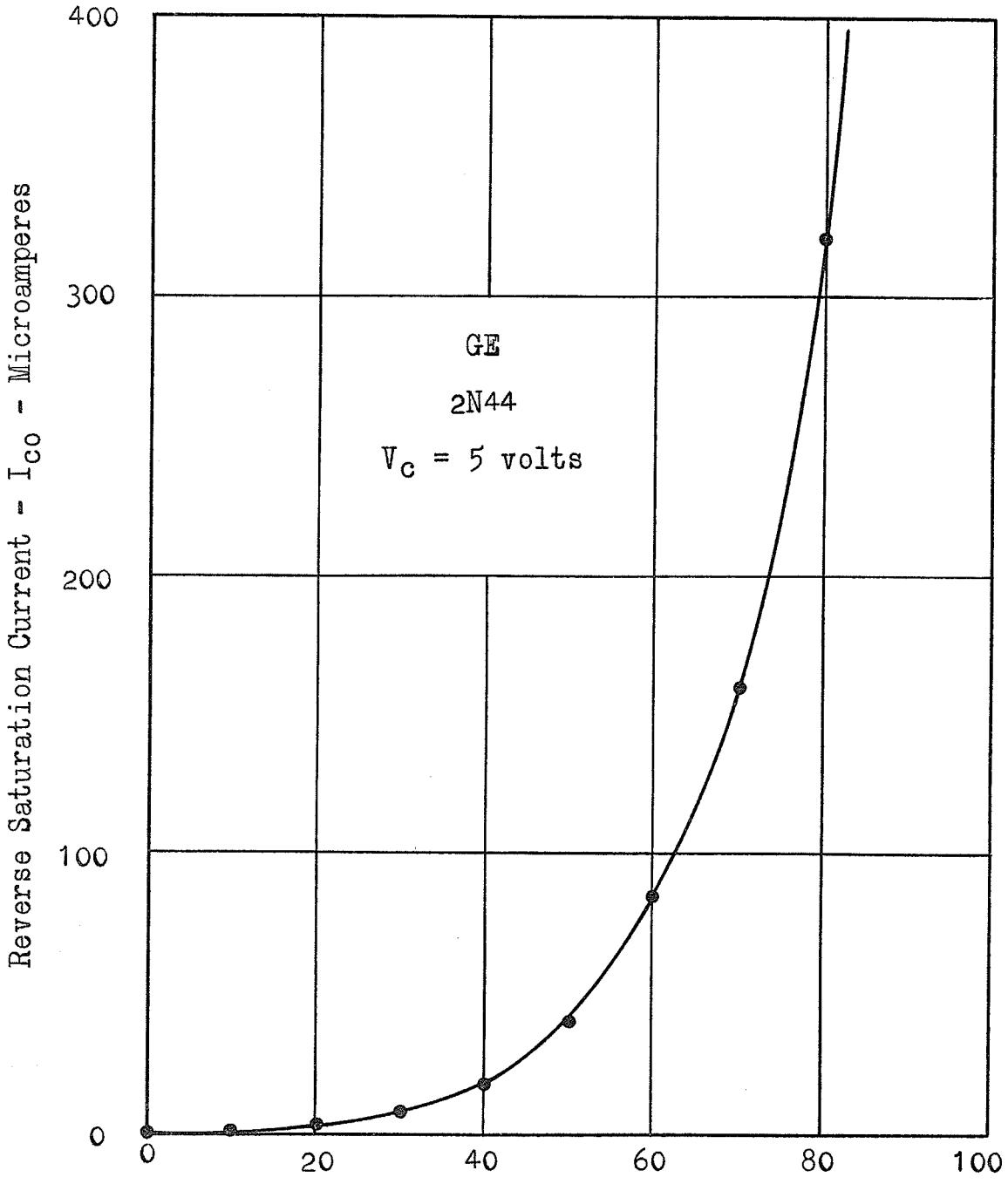
3 - R. F. Shea ed Transistor Circuit Engineering, Wiley 1957, Page 62.
4 - Ibid, Page 64.
5 - Ibid, Page 142.



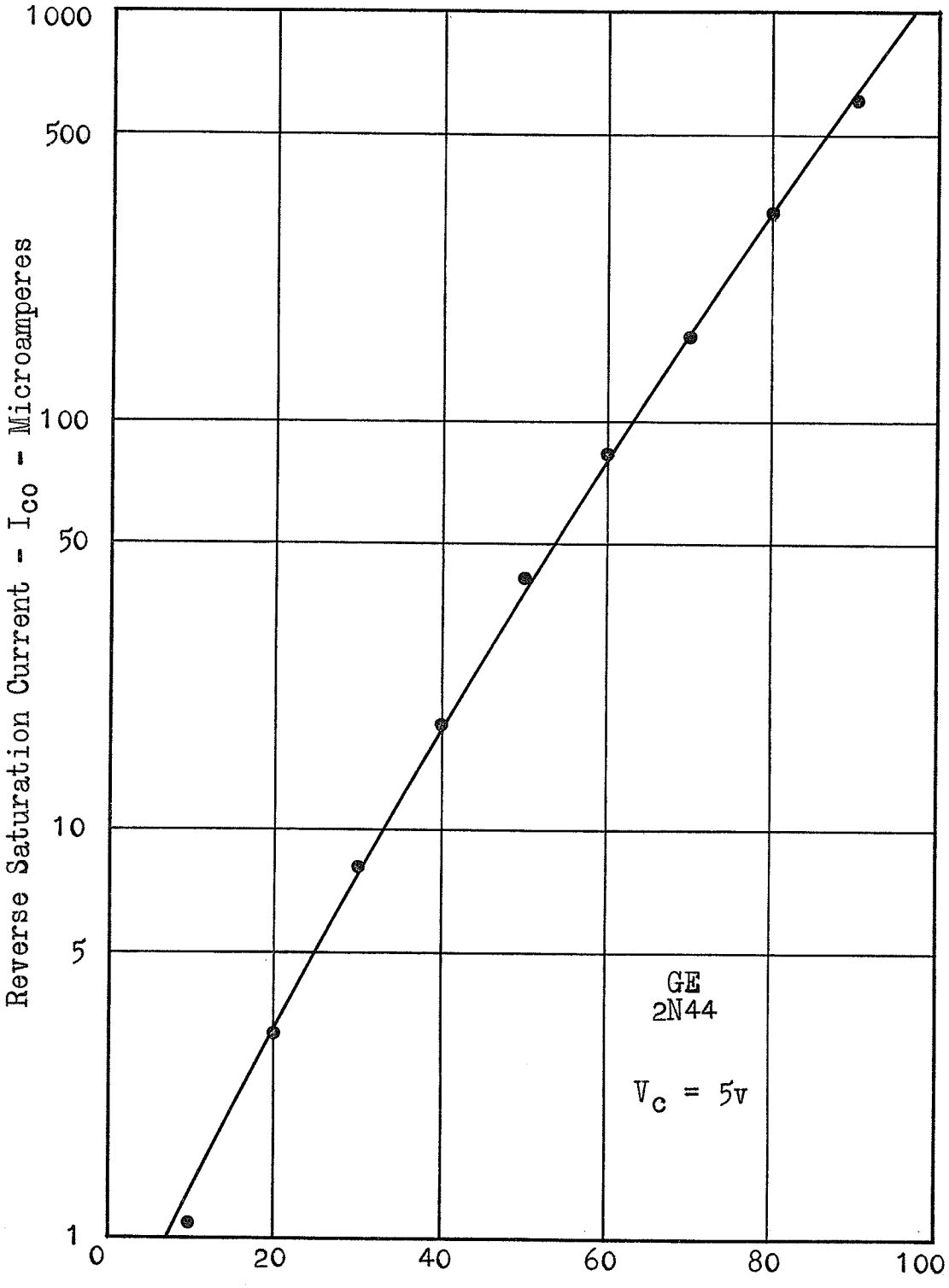
GRAPH 1 COMMON-EMITTER STATIC COLLECTOR CHARACTERISTICS



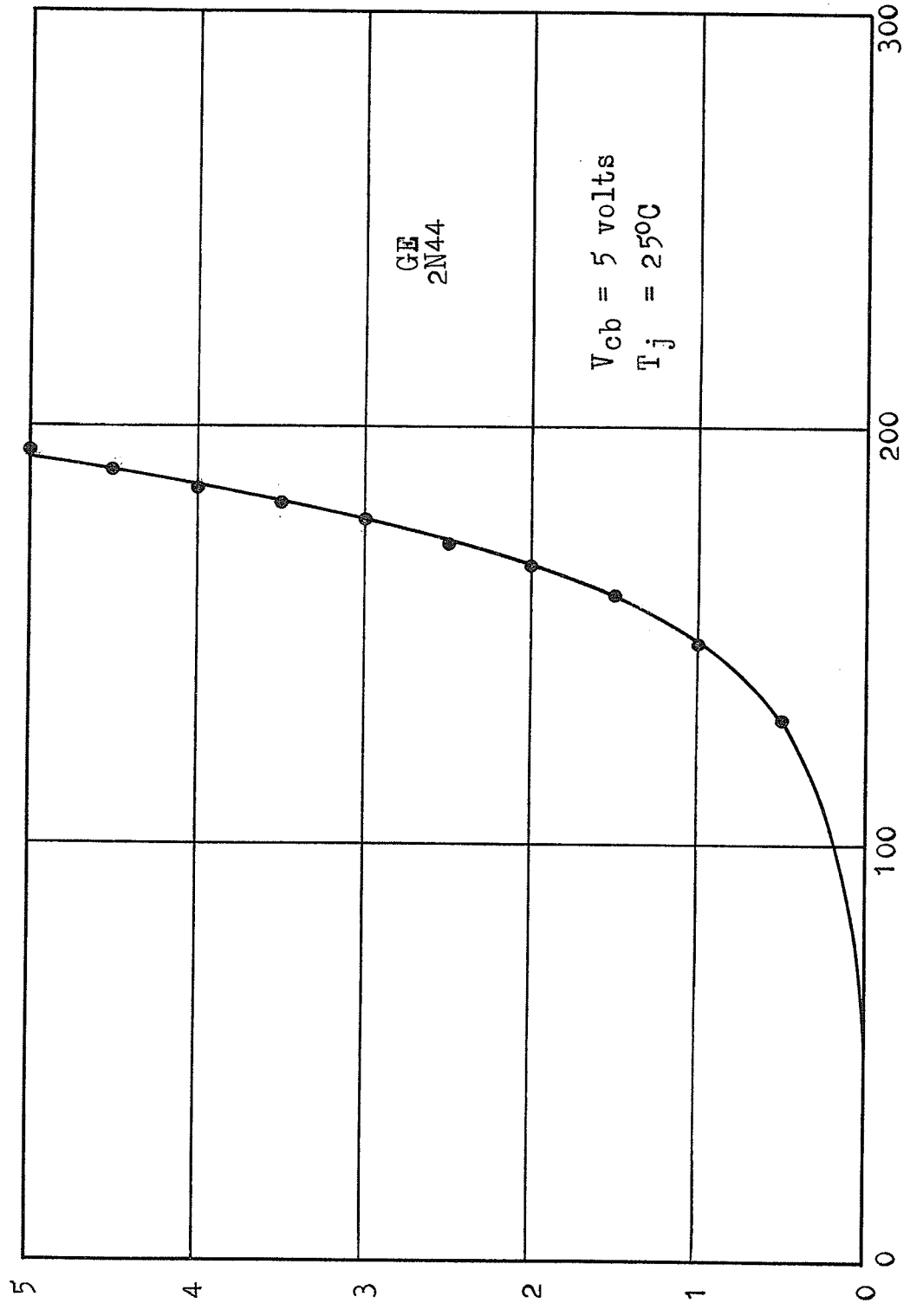
GRAPH 2 VARIATION OF I_{co} WITH COLLECTOR VOLTAGE



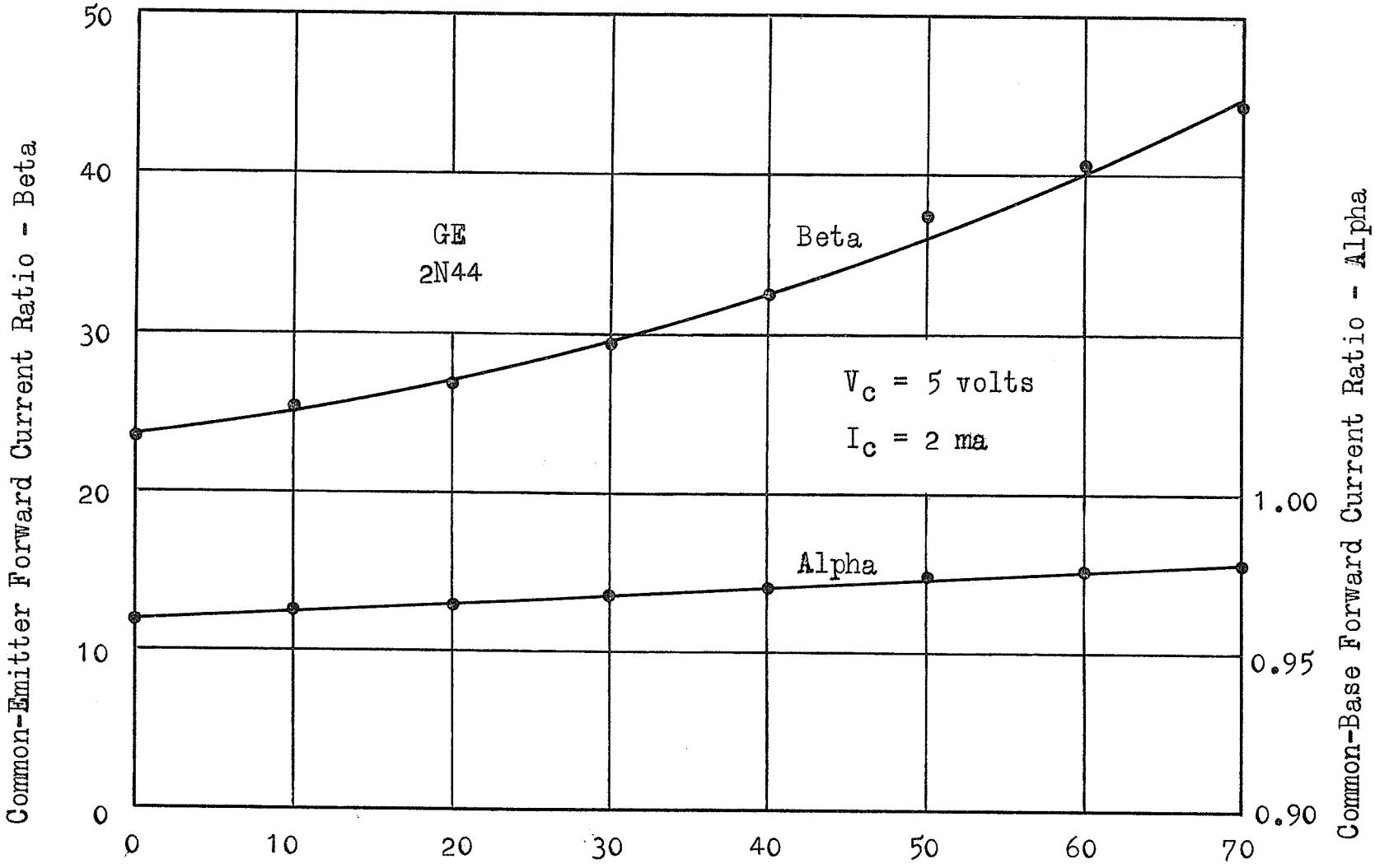
GRAPH 3 VARIATION OF I_{co} WITH JUNCTION TEMPERATURE



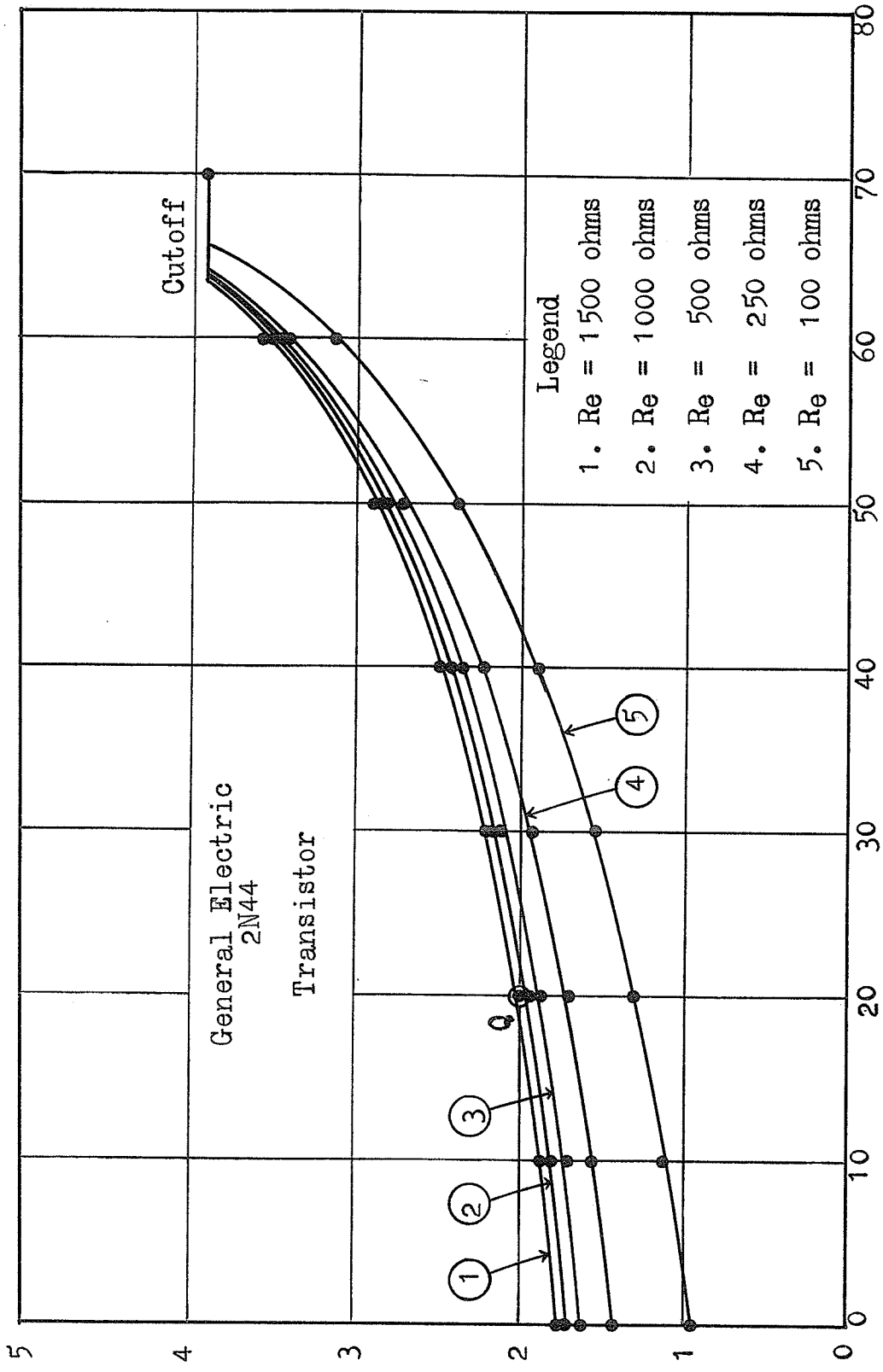
GRAPH 4 VARIATION OF I_{co} WITH JUNCTION TEMPERATURE



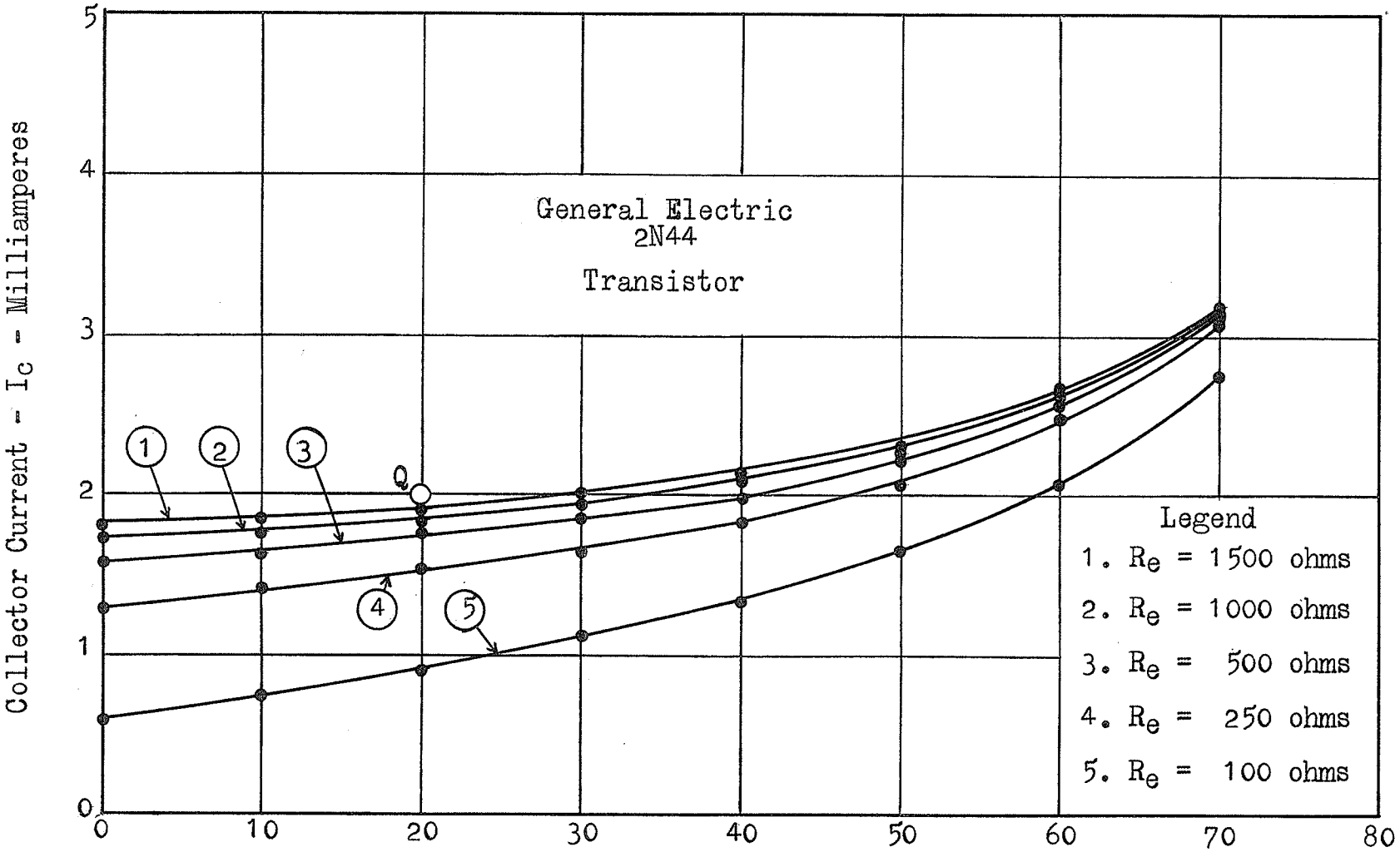
GRAPH 5 COMMON-BASE INPUT CHARACTERISTIC



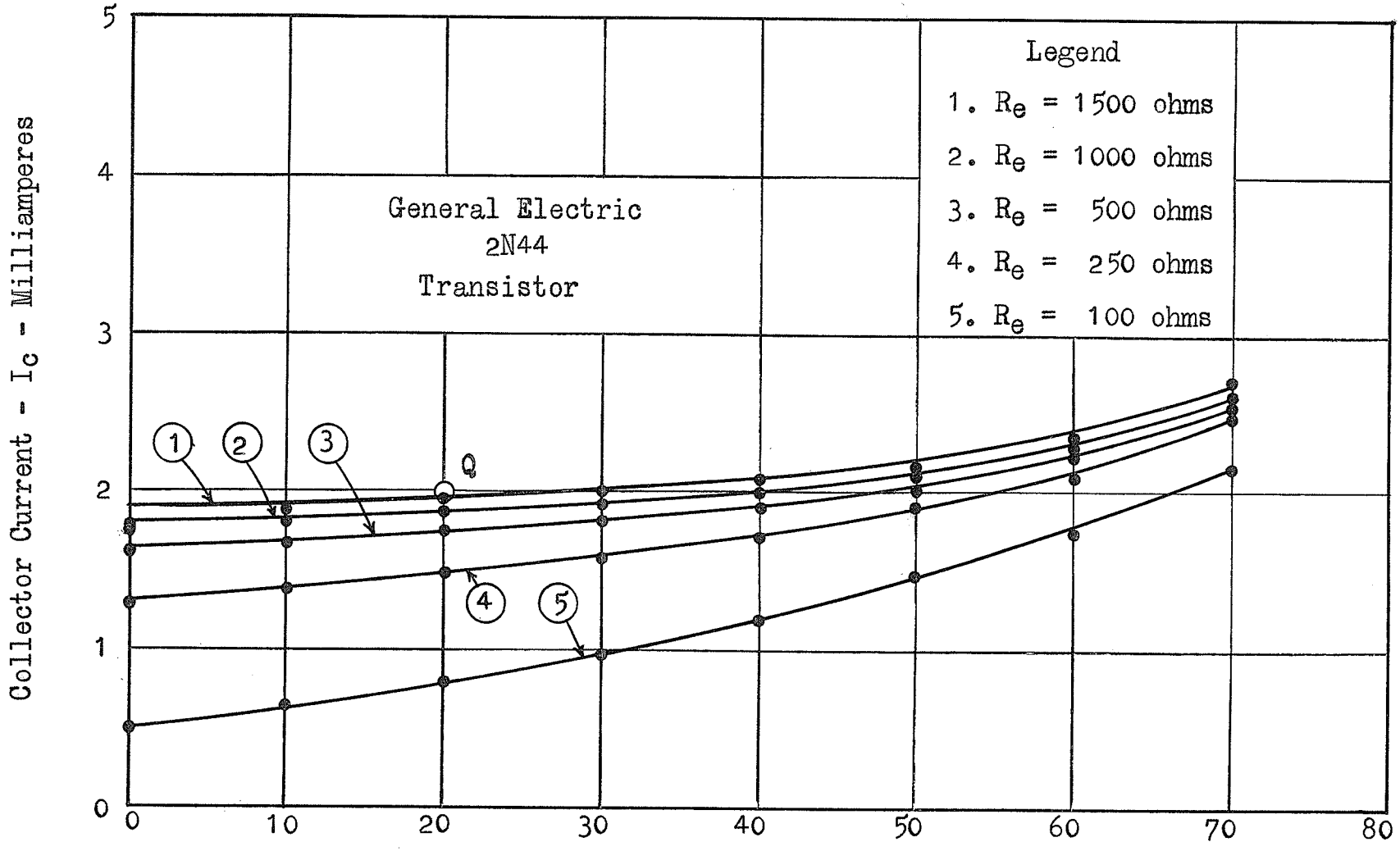
GRAPH 6 VARIATION IN ALPHA AND BETA WITH JUNCTION TEMPERATURE



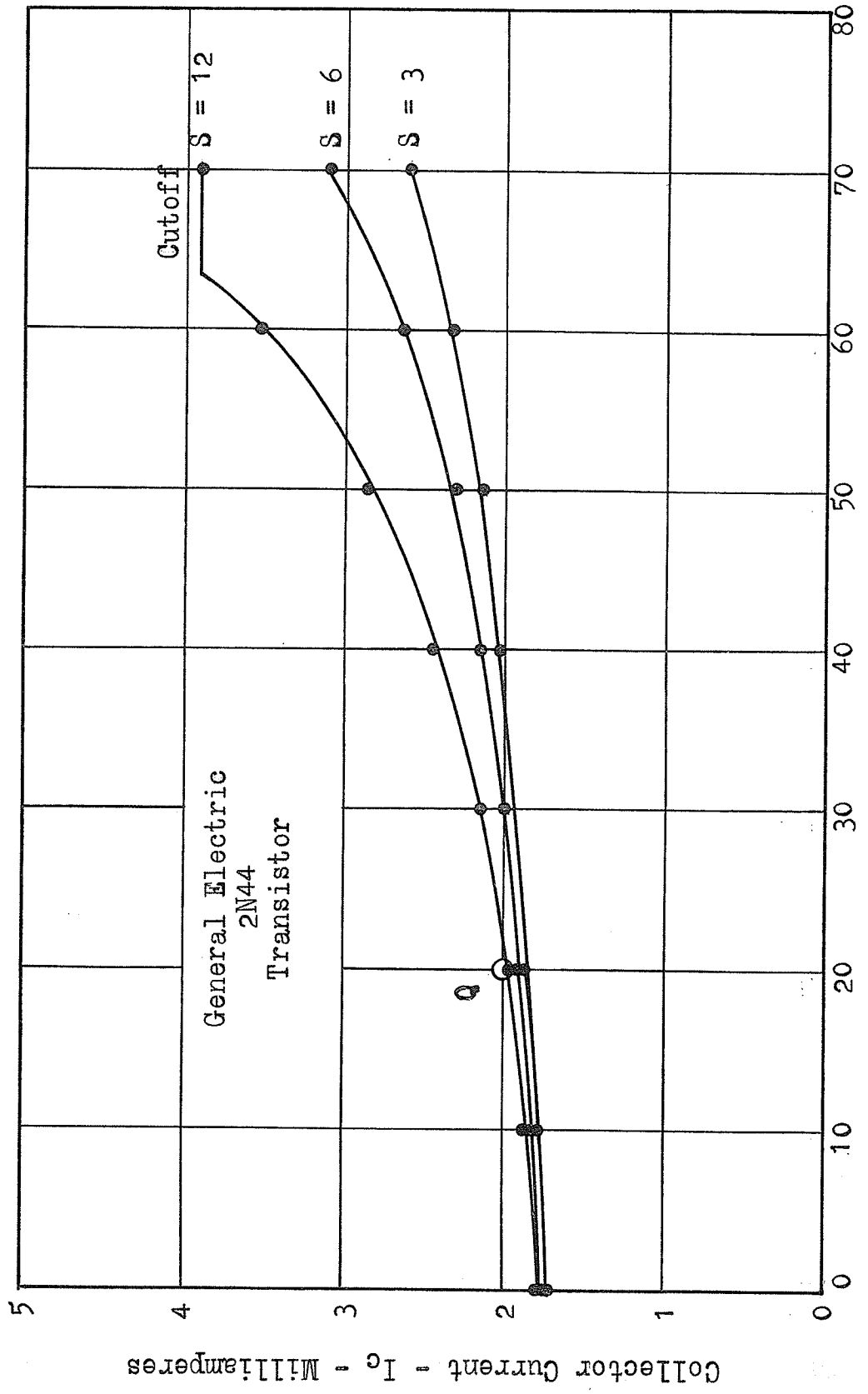
GRAPH 7 VARIATION OF I_c WITH JUNCTION TEMPERATURE, S = 12



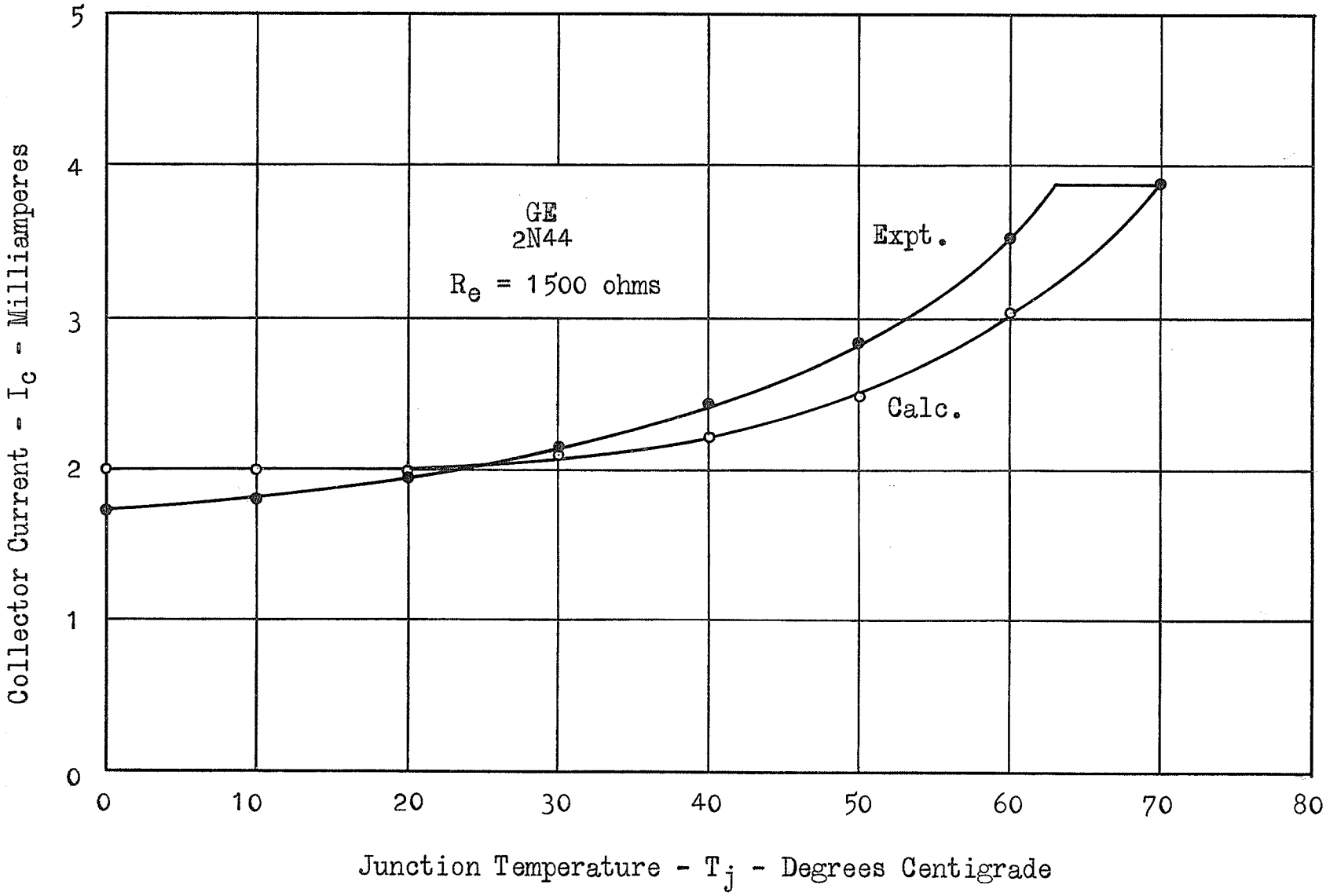
GRAPH 8 VARIATION OF I_c WITH JUNCTION TEMPERATURE, S = 6



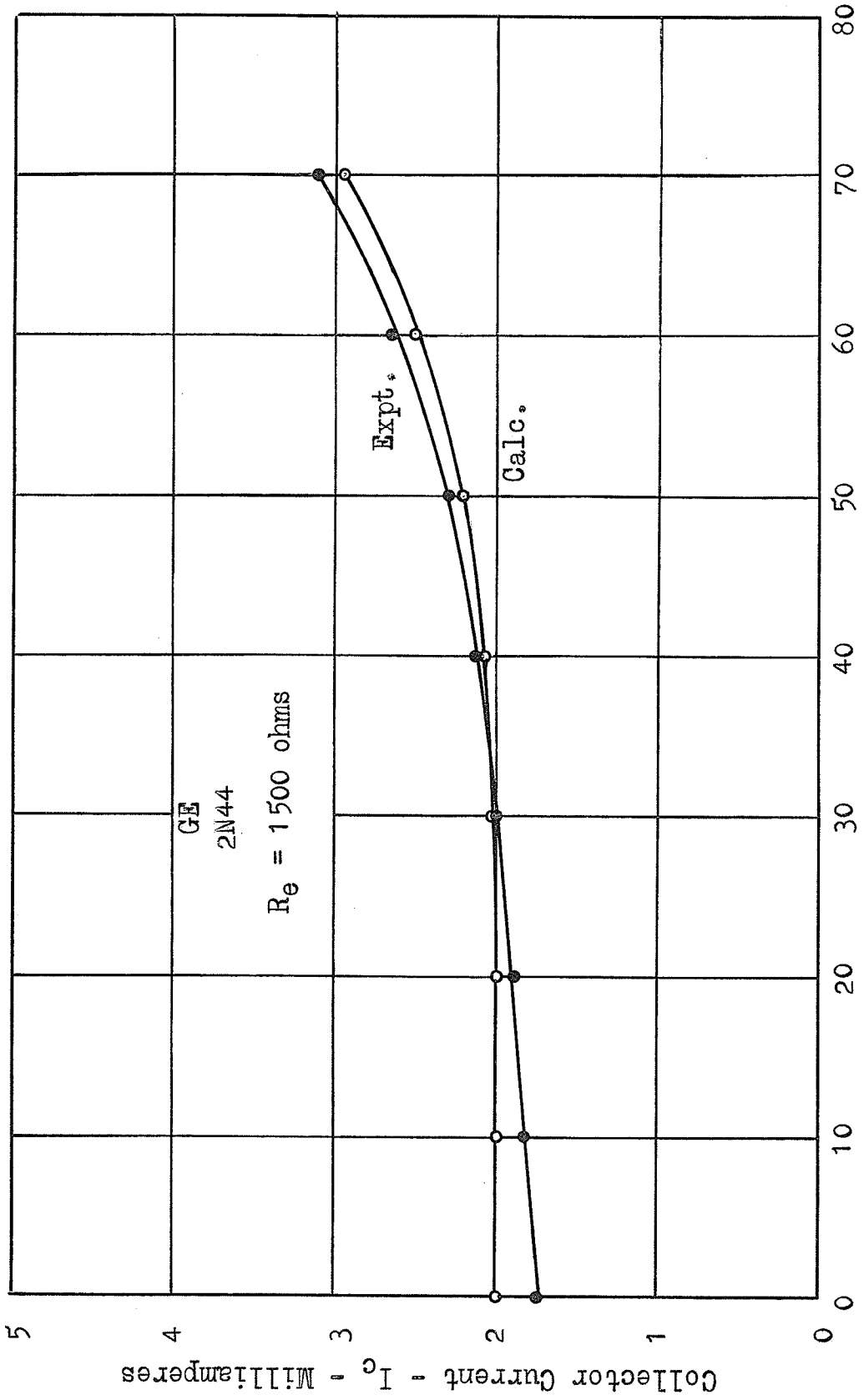
GRAPH 9 VARIATION OF I_c WITH JUNCTION TEMPERATURE, S = 3



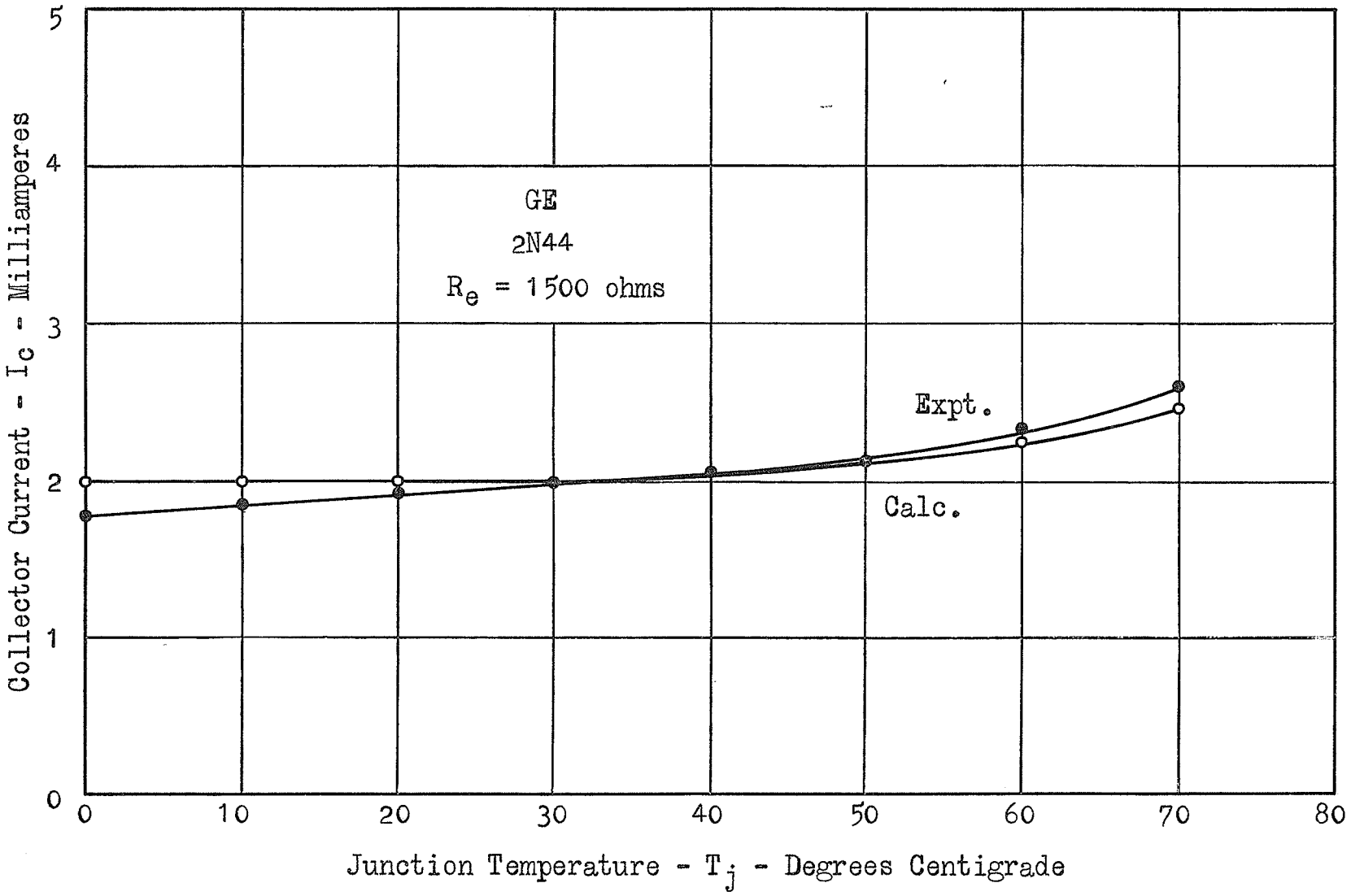
GRAPH 10 VARIATION OF I_C WITH JUNCTION TEMPERATURE, S = 12, 6 AND 3, R_e = 1500 ohms



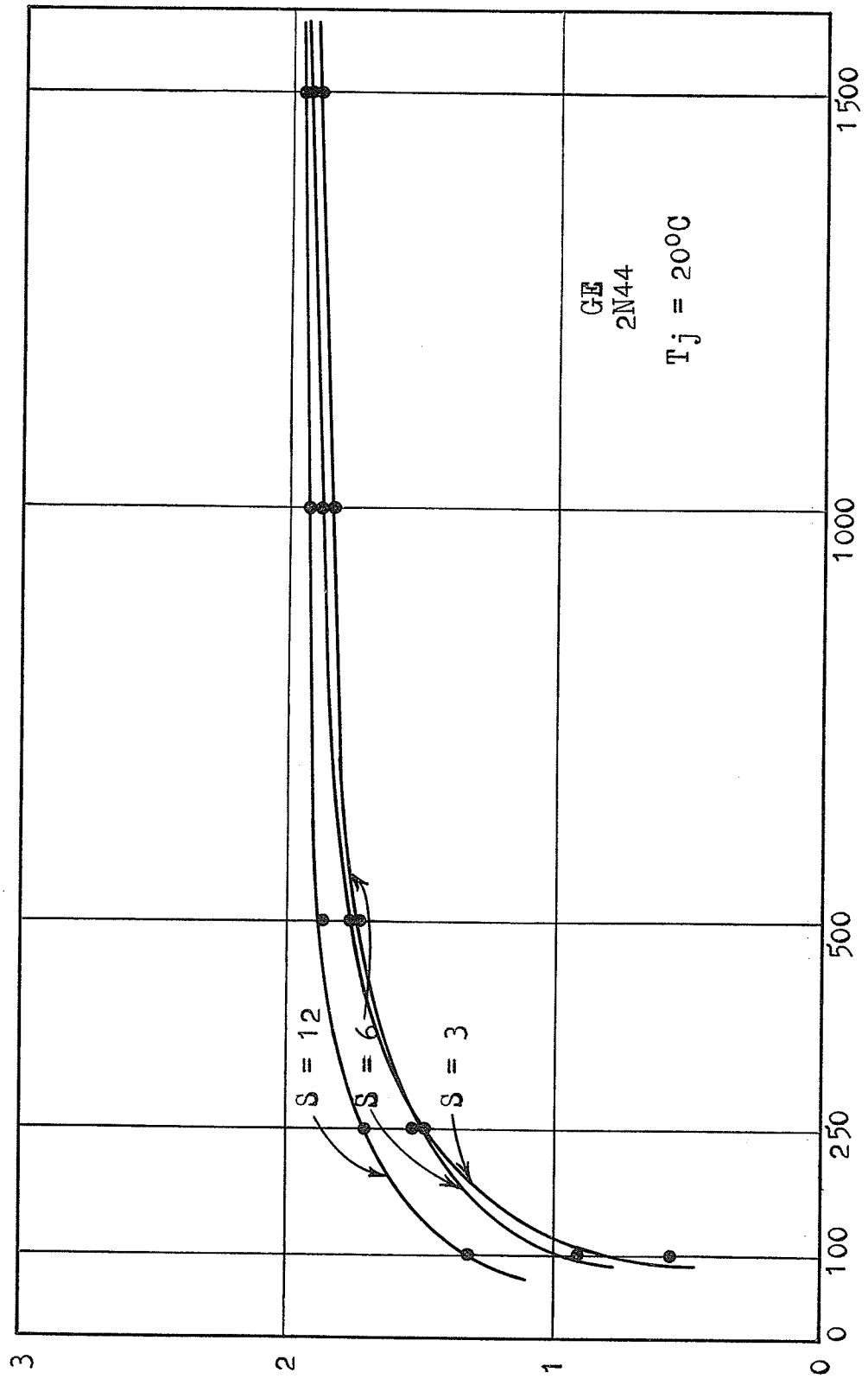
GRAPH 11 COMPARISON BETWEEN EXPERIMENTAL AND CALCULATED CHANGE IN I_c FOR S = 12



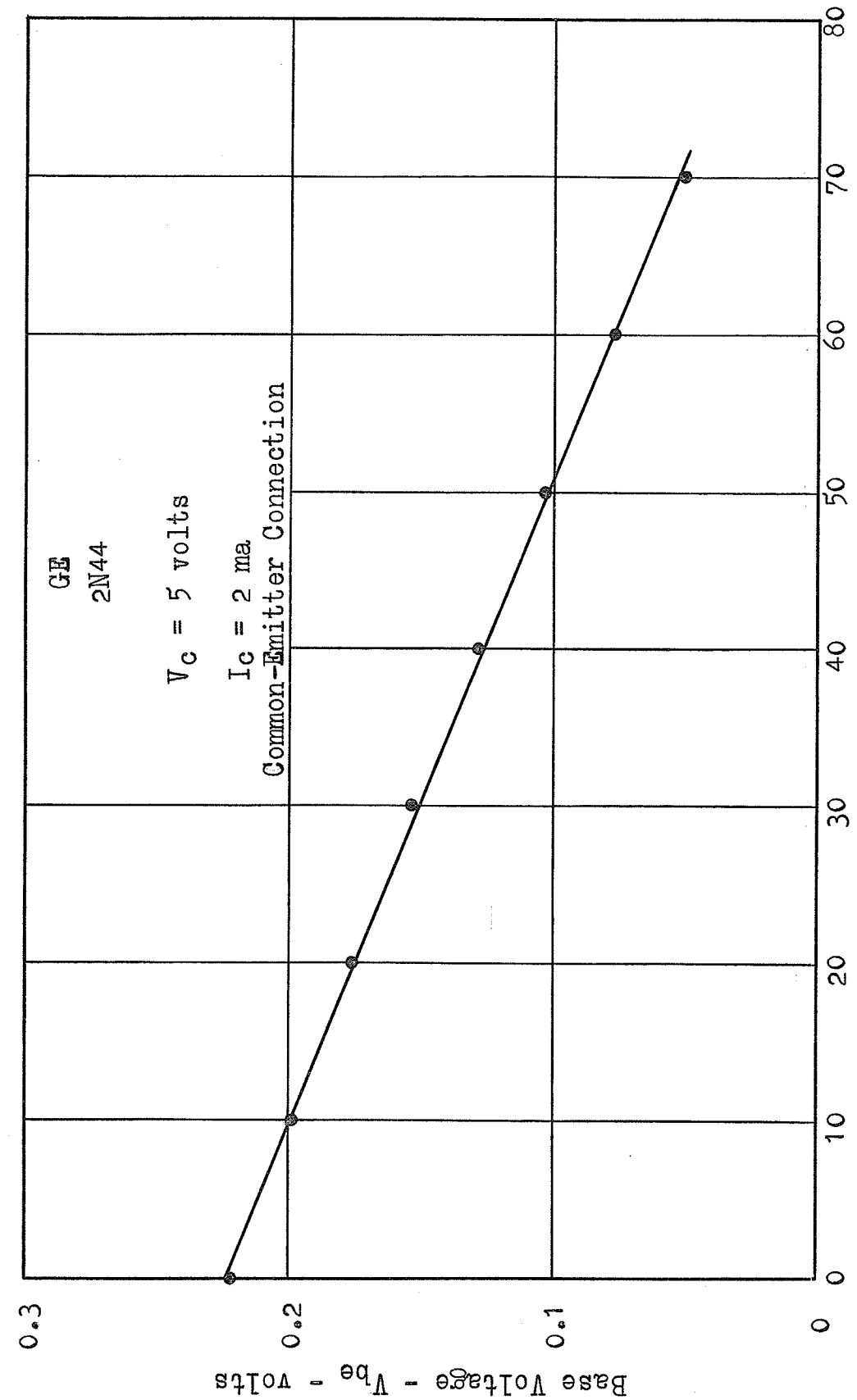
GRAPH 12 COMPARISON BETWEEN EXPERIMENTAL AND CALCULATED CHANGE IN I_c FOR S = 6



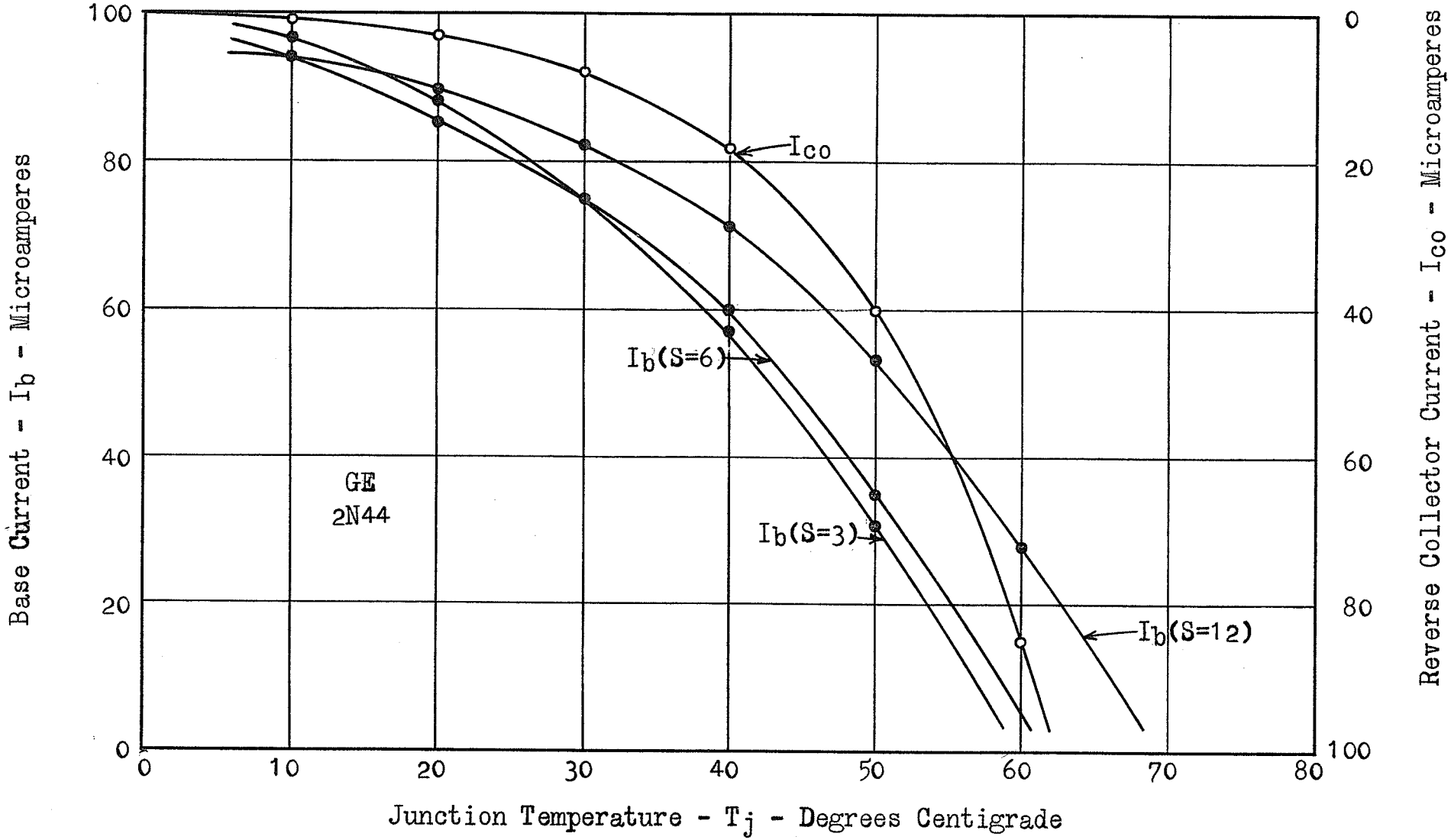
GRAPH 13 COMPARISON BETWEEN EXPERIMENTAL AND CALCULATED CHANGE IN I_c FOR S = 3



GRAPH 14 VARIATION IN QUIESCENT VALUE OF I_c FOR S = 12, S = 6 & S = 3



GRAPH 15 VARIATION OF BASE VOLTAGE WITH JUNCTION TEMPERATURE FOR CONSTANT COLLECTOR CURRENT



GRAPH 16 VARIATION OF I_b AND I_{co} WITH JUNCTION TEMPERATURE FOR S = 12, 6 AND 3, R_e = 1500 OHMS

TABLE 4

COMMON-EMITTER STATIC COLLECTOR CHARACTERISTIC CURVE DATA

GE 2N44 Transistor

I_c versus V_c for constant I_b, $T_a = 25^oC$

$V_c \rightarrow$ Volts	1.00	2.00	4.00	6.00	8.00	10.00
I_b μa	I_c ma	I_c ma	I_c ma	I_c ma	I_c ma	I_c ma
0	0.05	0.06	0.06	0.06	0.06	0.07
25	0.49	0.50	0.53	0.56	0.58	0.60
50	0.90	0.95	1.00	1.05	1.10	1.13
75	1.40	1.42	1.50	1.60	1.65	1.73
100	1.90	2.05	2.15	2.24	2.34	2.43
125	2.51	2.60	2.79	2.95	3.10	3.30
150	3.08	3.20	3.45	3.72	3.90	4.15
175	3.68	3.82	4.15	4.45	4.82	5.10
200	4.29	4.50	4.80	5.20	5.60	6.00

TABLE 5

REVERSE SATURATION CURRENT-COLLECTOR VOLTAGE CURVE DATA

GE 2N44 Transistor

I_{co} versus V_c for Constant $T_j = 25^{o}C$

V_c Volts	I_{co} μa
1	4.9
2	5.1
3	5.2
4	5.4
5	5.6
6	5.8
7	5.9
8	6.0
9	6.1
10	6.2

TABLE 6

REVERSE SATURATION CURRENT CURVE DATA

GE 2N44 Transistor

I_{co} versus T_j for constant V_c = 5 volts

T_j °C	I_{co} μa
0	0.5
10	1.1
20	3.2
30	8.0
40	18.2
50	40.4
60	85.1
70	160
80	321
90	605
100	1050

TABLE 7

COMMON-BASE INPUT CHARACTERISTIC CURVE DATA

GE 2N44

I_e versus V_{eb} for $T_j = 25^{\circ}C$ and $V_{cb} = 5$ volts

I_e ma	V_{eb} mv
0	0
0.5	130
1.0	148
1.5	160
2.0	167
2.5	172
3.0	178
3.5	182
4.0	185
4.5	190
5.0	195

TABLE 8

VARIATION OF ALPHA BETA AND GAMMA

WITH JUNCTION TEMPERATURE

GE 2N44

T_j	α	β	γ
0	0.959	23.4	24.4
10	0.962	25.3	26.3
20	0.964	26.8	27.8
30	0.967	29.3	30.3
40	0.970	32.3	33.3
50	0.974	37.5	38.5
60	0.976	40.7	41.6
70	0.978	44.5	45.5
80	0.980	49.0	50.0

TABLE 9

VARIATION OF OPERATING POINT WITH JUNCTION TEMPERATURE

GE 2N44 Transistor

R_e = 1500 ohms

	S = 12 R_a = 100000 ohms R_b = 57500 ohms			S = 6 R_a = 16600 ohms R_b = 25500 ohms			S = 3 R_a = 5310 ohms R_b = 10100 ohms		
T_j °C	Ib μa	Vc Volts	Ic ma	Ib μa	Vc Volts	Ic ma	Ib μa	Vc Volts	Ic ma
0	98	5.71	1.72	102	5.6	1.76	105	5.50	1.78
10	94	5.56	1.80	94	5.45	1.83	97	5.35	1.85
20	89	5.10	1.95	85	5.25	1.89	88	5.29	1.92
30	82	4.62	2.15	75	5.00	2.00	75	5.00	2.00
40	71	3.96	2.42	60	4.69	2.13	58	4.87	2.05
50	53	2.87	2.85	35	4.20	2.30	31	4.64	2.13
60	28	1.21	3.52	- 7	3.40	2.65	-19	4.23	2.32
70	14	0.10	3.90	-71	2.25	3.10	-100	3.78	2.60

TABLE 10

VARIATION OF OPERATING POINT WITH JUNCTION TEMPERATURE

GE 2N44 Transistor

R_e = 1000 ohms

	S = 12 R_a = 42000 ohms Rb = 57500 ohms			S = 6 R_a = 9120 ohms Rb = 25500 ohms			S = 3 R_a = 3020 ohms Rb = 10100 ohms		
T_j °C	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma
0	97	5.80	1.70	100	5.78	1.70	105	5.65	1.76
10	93	5.58	1.78	93	5.60	1.76	95	5.50	1.82
20	87	5.20	1.92	85	5.40	1.83	86	5.35	1.86
30	80	4.63	2.13	75	5.20	1.92	74	5.20	1.92
40	71	4.03	2.40	60	4.78	2.07	57	5.00	2.00
50	55	2.97	2.80	36	4.30	2.27	31	4.71	2.10
60	28	1.28	3.48	-5	3.52	2.60	-17	4.30	2.30
70	9	0.10	3.90	-78	2.19	3.13	-101	3.33	2.70

TABLE 11

VARIATION OF OPERATING POINT WITH JUNCTION TEMPERATURE

GE 2N44 Transistor

R_e = 500 ohms

	S = 12 R_a = 15800 ohms R_b = 57500 ohms			S = 6 R_a = 3870 ohms R_b = 25500 ohms			S = 3 R_a = 1310 ohms R_b = 10100 ohms		
T_j °C	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma
0	93	6.20	1.58	93	6.10	1.56	94	6.00	1.60
10	89	5.80	1.70	87	6.00	1.62	86	5.80	1.68
20	85	5.40	1.86	79	5.70	1.72	79	5.70	1.73
30	78	4.80	2.10	70	5.41	1.83	68	5.50	1.81
40	69	4.17	2.34	56	5.10	1.97	52	5.25	1.90
50	53	3.00	2.80	33	4.50	2.20	26	4.97	2.01
60	26	1.23	3.50	-9	3.67	2.53	-20	4.50	2.21
70	9	0.10	3.90	-86	2.10	3.17	-98	3.76	2.51

TABLE 12

VARIATION OF OPERATING POINT

WITH JUNCTION TEMPERATURE

GE 2N44 Transistor

R_e = 250 ohms

	S = 12 R_a = 6900 ohms R_b = 57500 ohms			S = 6 R_a = 1800 ohms R_b = 25500 ohms			S = 3 R_a = 615 ohms R_b = 10100 ohms		
T_j °C	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma
0	84	6.56	1.40	78	6.80	1.28	78	7.27	1.29
10	81	6.15	1.56	75	6.50	1.40	75	6.57	1.39
20	78	5.75	1.70	70	6.23	1.51	69	6.30	1.49
30	72	5.29	1.91	62	5.92	1.63	61	6.10	1.59
40	65	4.46	2.21	50	5.48	1.81	47	5.80	1.71
50	49	3.30	2.70	29	4.86	2.05	22	5.30	1.90
60	23	1.50	3.40	-17	3.80	2.49	-24	4.80	2.11
70	2	0.10	3.90	-80	2.50	3.01	-100	3.80	2.48

TABLE 13

VARIATION OF OPERATING POINT

WITH JUNCTION TEMPERATURE

GE 2N44 Transistor

R_e = 100 ohms

	S = 12 R_a = 2640 ohms R_b = 57500 ohms			S = 6 R_a = 690 ohms R_b = 25500 ohms			S = 3 R_a = 238 ohms R_b = 10100 ohms		
T_j °C	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma	I_b μa	V_c Volts	I_c ma
0	60	7.60	0.96	40	8.57	0.58	35	8.78	0.50
10	61	7.22	1.11	43	8.20	0.73	39	8.46	0.65
20	60	6.75	1.30	44	7.77	0.90	40	8.00	0.80
30	58	6.15	1.54	42	7.28	1.10	37	7.60	0.99
40	52	5.30	1.89	34	6.71	1.31	28	7.02	1.20
50	39	4.10	2.37	15	5.87	1.66	8	6.32	1.48
60	14	2.23	3.10	-22	4.81	2.08	-39	5.60	1.76
70	-13	0.10	3.90	-90	3.18	2.74	-104	4.58	2.16

TABLE 14

COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL VALUES OF I_c

ΔI_c for 40°C change in T_j

	Calculated	Experimental	
S = 12	ΔI_c = 1.00 ma	R_e = 1500 ohms	ΔI_c = 1.57 ma
		R_e = 1000 ohms	ΔI_c = 1.56 ma
		R_e = 500 ohms	ΔI_c = 1.64 ma
		R_e = 250 ohms	ΔI_c = 1.70 ma
		R_e = 100 ohms	ΔI_c = 1.80 ma
S = 6	ΔI_c = 0.50 ma	R_e = 1500 ohms	ΔI_c = 0.76 ma
		R_e = 1000 ohms	ΔI_c = 0.77 ma
		R_e = 500 ohms	ΔI_c = 0.81 ma
		R_e = 250 ohms	ΔI_c = 0.98 ma
		R_e = 100 ohms	ΔI_c = 1.18 ma
S = 3	ΔI_c = 0.25 ma	R_e = 1500 ohms	ΔI_c = 0.40 ma
		R_e = 1000 ohms	ΔI_c = 0.44 ma
		R_e = 500 ohms	ΔI_c = 0.48 ma
		R_e = 250 ohms	ΔI_c = 0.62 ma
		R_e = 100 ohms	ΔI_c = 0.96 ma

TABLE 15

VARIATION OF BASE VOLTAGE WITH JUNCTION TEMPERATURE COMMON-EMITTER CONNECTION

GE 2N44 Transistor

V_b versus T_j, for constant V_c = 5 volts, I_c = 2 ma

T_j °C	I_b μa	V_b Volts
0	109	0.222
10	98	0.199
20	86	0.176
30	73	0.153
40	56	0.128
50	26	0.103
60	-27	0.077
70	-115	0.050

Average

$\Delta V_b = 0.0246$

APPENDICES

APPENDIX A

REVERSE SATURATION CURRENTS

A. 1 Collector Saturation Current, I_{co}

I_{co} is the reverse saturation current that flows from base to collector (for PNP transistor) when the collector-base diode is biased in the reverse direction with the emitter terminal open-circuited.

The circuit shown in Figure A.1 may be used to measure I_{co}.

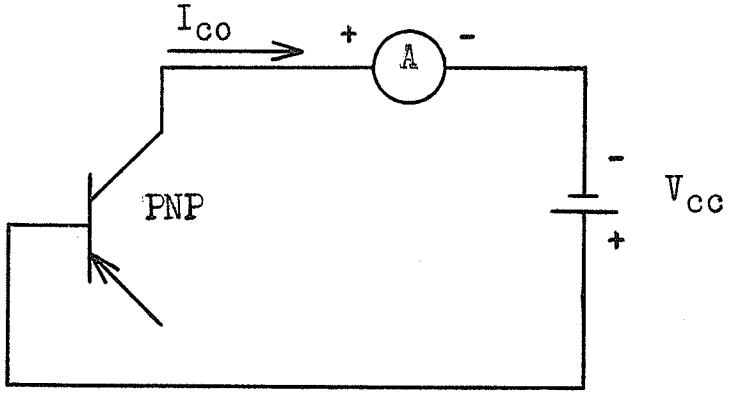


FIGURE A.1

CIRCUIT FOR THE MEASUREMENT OF I_{co}

I_{co} is due to the presence of minority current carriers in the base and collector regions. These minority carriers are thermally generated hole-electron pairs and consequently the magnitude of I_{co} will depend on the junction temperature. A reverse collector voltage of approximately one-tenth of a volt is sufficient to cause collector saturation. After saturation the thermally generated part of I_{co} is independent of collector volt-

age. The base-collector diode, however, has a high resistance leakage path over the surface of the transistor. This leakage path conducts a small current which varies directly with collector voltage. The reverse saturation current and leakage current combine to give the total reverse saturation current.

The variation of reverse saturation current with collector voltage, for a typical germanium transistor, is shown in Figure A.2. (See Graph 2 , Page 61 also).

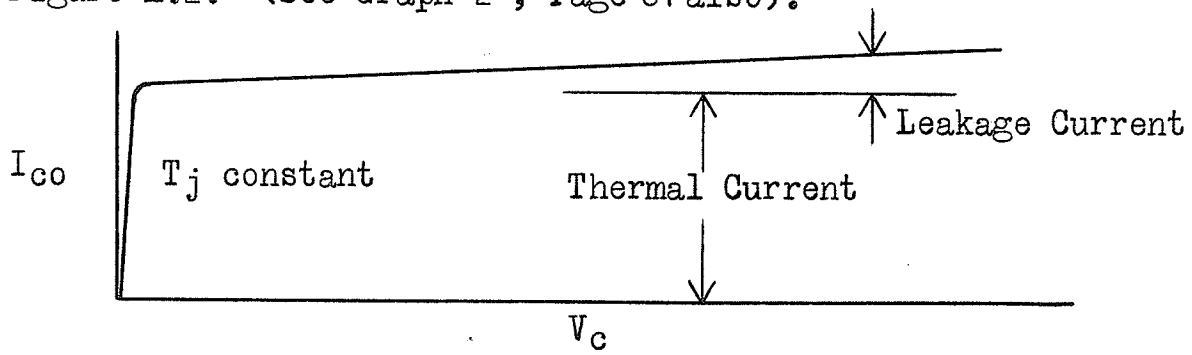


FIGURE A.2

VARIATION OF I_{co} WITH COLLECTOR VOLTAGE

For constant collector voltage and increasing junction temperature I_{co} will rise exponentially at a rate of approximately ten percent per degree Centigrade for germanium transistors.

Over a limited temperature range I_{co} has been found experimentally to vary according to the following expression:[1]

$$I_{co} = I_a e^{b(T_j - T_a)} \qquad \text{A.1}$$

---

1 - L. B. Arguimbau and R. B. Adler, Vacuum Tube Circuits and Transistors, Wiley 1956, P. 176.

where T_j = junction temperature,

T_a = ambient temperature,

I_a = I_{co} value at T_a,

b = a constant for the transistor.

The variation of I_{co} with junction temperature, for a typical germanium transistor, is shown in Figure A.3. (See Graph 3 , Page 62 also).

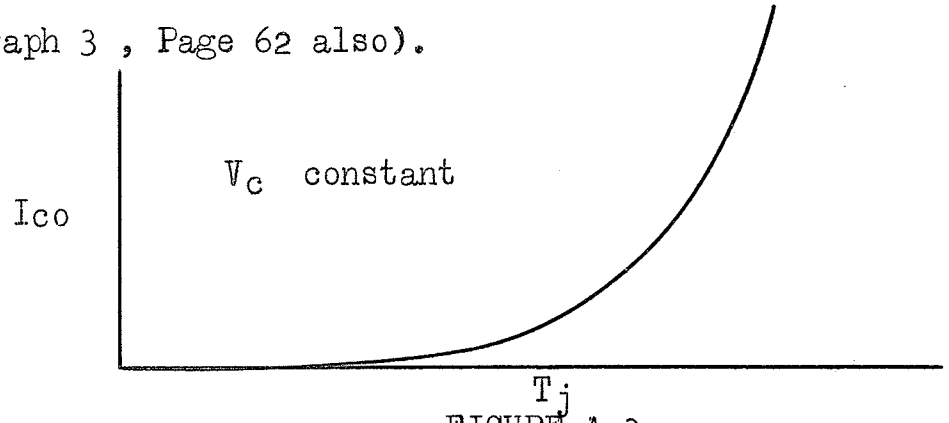


FIGURE A.3

VARIATION OF I_{co} WITH JUNCTION TEMPERATURE

The value of I_{co} at room temperature (25°C) depends on the construction of the transistor.[2] A list of various transistors with their I_{co} values is shown on Table 2, Page 11.

I_{co} is an uncontrollable current that does not perform any useful function in transistor operation.

A. 2 Collector Saturation Current, I_{eo}

I_{eo} is that collector saturation current that flows from

2 - R. D. Middlebrook, Junction Transistor Theory, Wiley 1957, P. 175.

emitter to collector when the base is open-circuited.

The circuit shown in Figure A.4 may be used to measure I_{eo}.

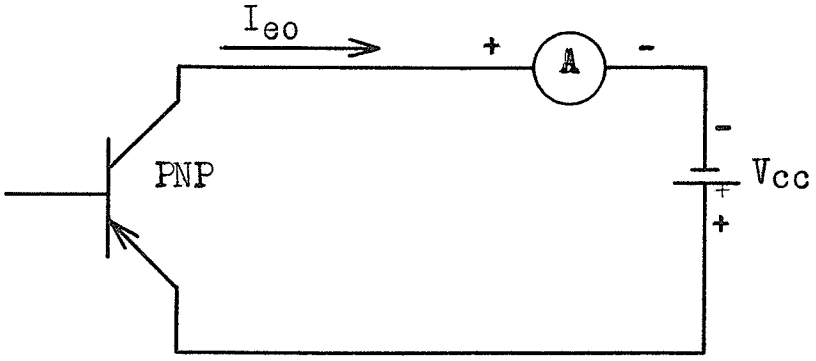


FIGURE A.4

CIRCUIT FOR MEASUREMENT OF I_{eo}

I_{eo} is the collector current that flows due to the presence of an internally generated base current I_{co}.[3] The relation between I_{co} and I_{eo} may be found from equation 4.4, Page 19. When $I_b = 0$ this equation reduces to:

$$I_{eo} = \frac{I_{co}}{1-\alpha} \qquad \text{A.2}$$

The equivalent circuit showing the base injection effect of I_{co} in the open base connection is shown in Figure A.5.

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3 - L. P. Hunter, Handbook of Semiconductor Electronics, McGraw-Hill 1956, P. 11-50.

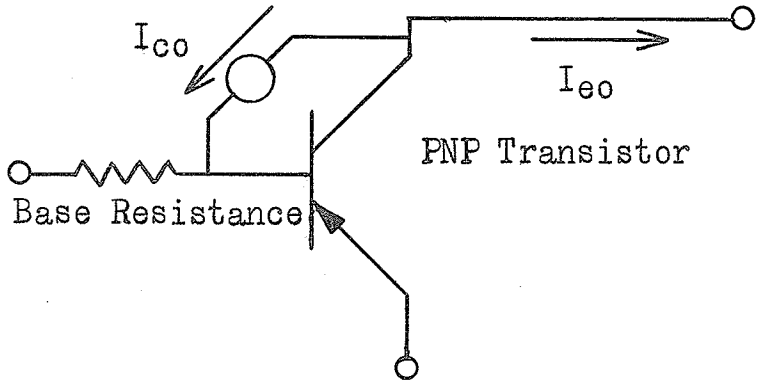

FIGURE A.5

BASE INJECTION EFFECT OF I_{co} ON I_{eo}[4]

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4 - Ibid, P. 11-50.

APPENDIX B

DEFINITIONS OF TERMS USED

B. 1 Transistor Terminology

Transistor terms, symbols and definitions have not yet become standardized; therefore a brief list of some of the more important terms and definitions is included here for reference. The most generally accepted symbols and terminology have been used.

B. 2 Transistor Currents

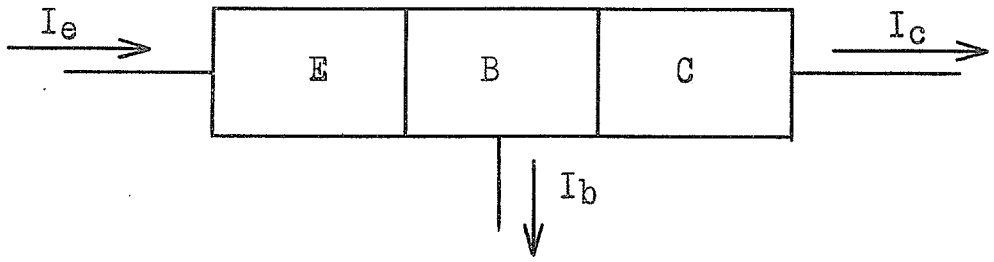

FIGURE B.1

CURRENTS IN A PNP TRANSISTOR

The currents refer to the direct current values. Current directions shown in Figure B.1 are for a PNP transistor. Current directions will be reversed for an NPN transistor.

Refer to Figure B.1:

I_c = collector current, the current in the collector lead

I_b = base current, the current in the base lead

I_e = emitter current, the current in the emitter lead

B. 3 Transistor Voltages

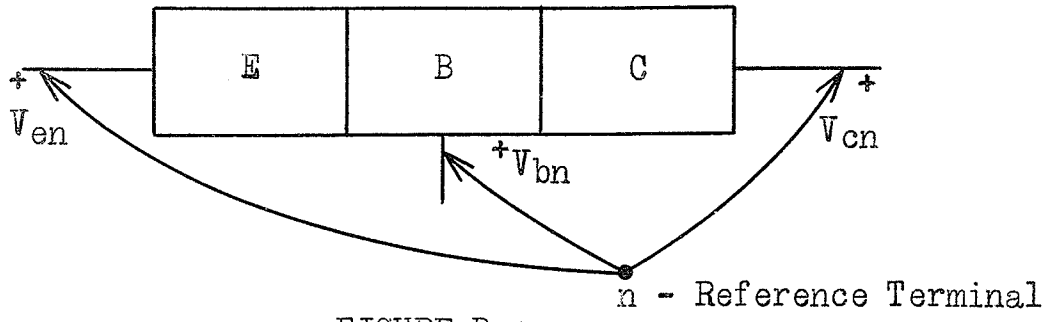

FIGURE B.2

VOLTAGES OF A PNP TRANSISTOR

The voltages refer to the direct current values. The voltages are measured from one transistor terminal to a reference terminal. The reference terminal will normally be the transistor terminal common to both the input and output circuits.

Refer to Figure B.2, assume that the emitter terminal is the common terminal:

V_{ce} = collector voltage, the voltage from collector to reference (emitter) terminal

V_{be} = base voltage, the voltage from base to reference (emitter) terminal

If it is obvious from the circuit configuration that the emitter is the reference terminal then the subscript

'$_e$' may be dropped and the collector and base voltages designated as V_c and V_b respectively.

B. 4 Operating Point, Q

The operating point is the point on the V_c-I_c output characteristic plane about which alternating-current signal operation takes place. The operating point is established by biasing the transistor with direct-current voltages and currents. The value of the operating point chosen for a particular circuit will depend on:

(1) the maximum value of signal voltage and current swings;

(2) the value of AC and DC load-line resistance;

(3) whether Class A, B or C operation is desired;

(4) the maximum values of collector dissipation and collector voltage and current ratings.

The operating point may also be called the quiescent point, the Q point or the standby point.

For a particular set of design specifications there will be an optimum value for the operating point; therefore any movement from the design position under dynamic operating conditions is undesirable.

B. 5 Ambient Air Temperature, T_a

The ambient air temperature is the temperature

of the air surrounding the transistor shell.

B. 6 Junction Temperature - T_j

The junction temperature is the temperature of the collector-base diode junction.

B. 7 Maximum Junction Temperature, T_{max}

The maximum junction temperature is the maximum value of the junction temperature recommended by the transistor manufacturer and represents the maximum safe operating temperature.

T_{max} for germanium transistors will normally be from 50°C to 100°C depending on the transistor type (i.e. fused or grown junction) and enclosure construction.

B. 8 Collector Saturation Current, I_{co}

I_{co} is the reverse saturation current that flows from base to collector (for a PNP transistor) when the collector-base diode is biased in the reverse direction with the emitter open-circuited. Refer to Appendix A for a more detailed description of the nature of I_{co}.

B. 9 Collector Saturation Current, I_{eo}

I_{eo} is the reverse saturation current that flows from emitter to collector (for a PNP transistor) when the emitter and collector are connected in series with the base open-circuited. The collector is biased in the reverse direction. Refer to Appendix A for a more detailed description of the nature of I_{eo}.

B10. Common-Base Forward Current Ratio, α

Alpha (α) is the value of the short-circuit forward current ratio for the common-base connection and is defined as the ratio of collector current to emitter current. For junction transistors alpha is slightly less than unity.

$$\alpha = \frac{I_c}{I_e} \qquad \text{B.1}$$

B. 11 Common-Emitter Forward Current Ratio, β

Beta (β) is the value of the short-circuit forward current ratio for the common-emitter connection and is defined as the ratio of collector current to base current. For junction transistors beta may be as low as 10 or as high as 150 depending on the value of alpha.

$$\beta = \frac{I_c}{I_b} \qquad \text{B.2}$$

Alpha and beta are connected by the following relationship:

Refer to Figure B.1:

$$I_e = I_b + I_c \qquad \text{B.3}$$

From equation B.1:

$$\alpha I_e = I_c \qquad \text{B.4}$$

Substitute $\frac{I_c}{\alpha}$ from equation B.4 for I_e in equation B.3:

$$\frac{I_c}{\alpha} = I_b + I_c \qquad \text{B.5}$$

Rearrange the terms of equation B.5:

$$\frac{I_c}{I_b} = \frac{\alpha}{1-\alpha} = \beta \qquad \text{B.6}$$

B. 12 Gamma, γ

Gamma (γ) is defined as:

$$\gamma = \frac{1}{1-\alpha} \qquad \text{B.7}$$

Gamma has no physical significance in transistor operation and is simply an abbreviation for a term that occurs frequently in transistor circuit calculations.

B. 13 Hybrid Parameters

The transistor may be represented as an equivalent two-port network for small alternating-current signal operation. One very useful set of parameters for this representation are the hybrid or h parameters.

The h parameters are defined as follows:

h_i = input impedance

h_v = voltage feedback ratio

h_f = forward current ratio

h_o = output admittance

To indicate the circuit configuration for the h parameters the subscripts 'c', 'e' and 'b', are added to the symbols given about to indicate common-collector, common-emitter and common-base h parameters respectively. Thus h_{fe} is the forward current ratio in the common-emitter configuration.

B. 14 Common-base Input Characteristic

The common-base input characteristic represents the variation in emitter current with change in the emitter to base voltage when collector voltage is held constant.

Refer to Figure B.3 for a typical common-base input characteristic.

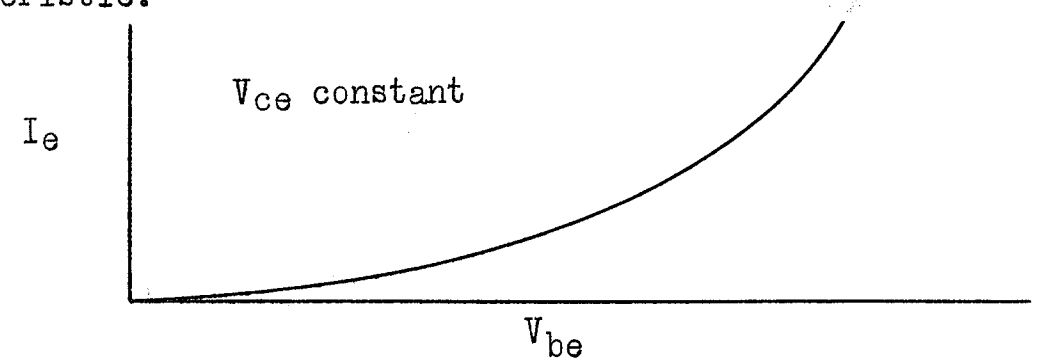

FIGURE B.3

COMMON-BASE INPUT CHARACTERISTIC

OF A PNP TRANSISTOR

B. 15 Stability Factor, S

The stability factor is defined as the change in collector current caused by a change in collector saturation current. The S factor is a differential quantity defined as:

$$S = \frac{dI_c}{dI_{co}} \qquad \text{B.8}$$

Incremental changes in I_c and I_{co} are normally used instead of the differential quantities and the stability factor is then defined as:

$$S = \frac{\Delta I_c}{\Delta I_{co}} \qquad \text{B.9}$$

S is a dimensionless number and may be calculated by determining the permissible variation in collector current and measuring the variation in collector saturation current for the design temperature variation. Refer to Appendix D for a more detailed discussion of the stability factors.

APPENDIX C

THERMAL RUNAWAY

C. 1 Thermal Runaway[1]

The normal quiescent collector dissipation of a transistor causes the junction temperature to rise above the ambient value. The increase in junction temperature results in an increase (exponential) in the reverse saturation current I_{CO}. The increase in I_{CO} causes a further increase in the junction temperature; which in turn raises I_{CO}. This cumulative heating cycle will continue until one of the following conditions results:

(1) the junction temperature becomes constant when the rate of collector dissipation equals the rate of heating and no further increase in I_{CO} takes place

(2) the junction temperature continues to rise, due to the cumulative heating cycle, until the transistor is destroyed by overheating.

Condition (1) represents a state of thermal equilibrium between the collector junction and the ambient air.

Condition (2) is a destructive process called thermal runaway.

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1 - L. P. Hunter, Handbook of Semiconductor Electronics, McGraw-Hill 1956, P. 13-12.

C. 2 Thermal Network

The junction temperature rise may be determined by setting up an electrical analogue circuit of the thermal network.

The circuit shown in Figure C.1 is a simple electrical analogue of the thermal network of a junction transistor.

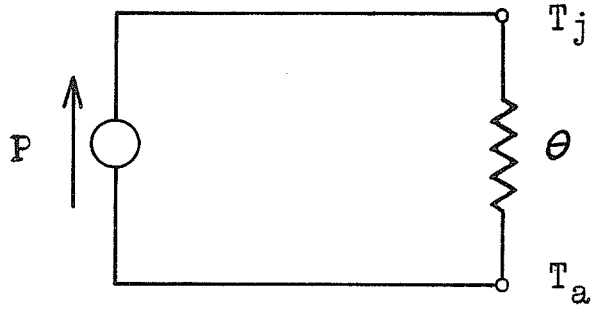

FIGURE C.1

THERMAL NETWORK OF A JUNCTION TRANSISTOR

In this equivalent circuit the collector dissipation is represented as a constant current source. The thermal path from collector to the ambient air is shown as a resistance and the difference in temperature between the collector junction and the ambient air by the potential drop across the resistance due to the current flow.

Refer to Figure C.1

$$T_j - T_a = P\theta \qquad \text{C.1}$$

where P = collector dissipation

θ = the thermal resistance between collector and ambient air

T_j = collector junction temperature

T_a = ambient air temperature

Equation C.1 may be written as:

$$T_j = T_a + P\theta \qquad C.2$$

The collector dissipation is:

$$P = V_c I_c \qquad C.3$$

where[2] $$I_c = \frac{\alpha V_{cc}}{R'} + SI_{co} \qquad C.4$$

and[3] $$I_{co} = I_a' \, e^{b(T_j - T_a')} \qquad C.5$$

Combining equations C.3, C.4 and C.5 and substituting the resultant value of P into equation C.2 then:

$$T_j = T_a + V_c\theta\frac{\alpha V_{cc}}{R'} + V_c\theta S \, I_a' e^{b(T_j - T_a')} \qquad C.6$$

C. 3 Thermal Runaway Conditions

The factors which result in thermal runaway may be determined by considering the collector heating process to take place in a series of infinitesimal increments. If the series is convergent an equilibrium state results (condition 1), if divergent thermal runaway takes place (condition 2).

To determine the runaway condition the derivative of T_j is taken with respect to T_a, using equation C.6.

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2 - See Equation 5.6, Page 35.

3 - See Appendix A. (Note that I_a' and T_a' are constants and are not functions of junction temperature.)

$$\frac{dT_j}{dT_a} = \frac{1}{1 - V_c \Theta bS \; I'_a \; e^{b(T_j - T'_a)}} \qquad C.7$$

which may be written:

$$\frac{dT_j}{dT_a} = \frac{1}{1 - V_c \Theta bS \; I_{co}} \qquad C.8$$

When the product of $V_c \Theta bS I_{co}$ is equal to or greater than one the derivative is infinite or negative and represents the runaway condition.

C. 4 Preventing Thermal Runaway

To prevent thermal runaway the product of $V_c \Theta bS I_{co}$ must be adjusted until it is less than one. Each of the factors will be known (or may be calculated); therefore the design may be checked to determine if a runaway condition exists.

Power amplifier designs must always be checked for thermal runaway conditions before the circuits are constructed for testing.

APPENDIX D

STABILITY FACTORS

D. 1 Definition of the S Factor

The stability factor, used in this investigation, is defined as the derivative of I_c with respect to I_{co}.

$$S = \frac{dI_c}{dI_{co}} \qquad D.1$$

This definition considers only one way of expressing the effect of varying temperature on the transistor circuit. However, it is the most useful and practical way of assessing the circuit performance with changing temperature.

Some other definitions of S are listed here for reference:

$$S = \frac{dI_e}{dI_{co}} \qquad D.2$$

$$S = \frac{dV_c}{dI_{co}} \qquad D.3$$

$$S = \frac{dI_c}{dT} \qquad D.4$$

$$S = \frac{dI_e}{dT} \qquad D.5$$

$$S = \frac{dV_c}{dT} \qquad D.6$$

These S factors have no advantages over the S factor used (equation D.1). They are included here because they appear in some of the references listed and also to show that the S definition used is not unique.

APPENDIX E

EXPERIMENTAL PROCEDURES

E. 1 Transistors

The following transistors were available for use in this investigation:

6 - GE 2N44	Tmax 100°C
6 - GE 2N78	Tmax 85°C
6 - GE 2N169	Tmax 75°C

The 2N44 is a fused junction transistor; the 2N78 and 2N169 are rate grown junction transistors.

The principal part of the experimental portion of this investigation was carried out using the 2N44 transistors because of their higher temperature rating. The data collected from tests performed on the other two transistor types was not included in this report.

E. 2 Meters

The following meters were used:

Voltmeter, General Radio model 1800A VTVM; Milliammeter, Weston Model 280; Microammeter, Tinsley Model SR1-45.

These instruments are standard laboratory meters with an inherent accuracy of 2% (of full scale value) for the volt meters and 1% (of full scale value) for the ammeters.

All meter scales could be read to three significant figures.

E. 3 Heating the Transistors

The transistors were heated in a temperature controlled oil bath. The oil was a low viscosity high dielectric strength transformer oil. The bath was heated by a controlled electric heating element; the oil being stirred during the heating cycle to maintain a uniform bath temperature.

The heating cycle was started with the oil temperature below 0°C. The bath was heated by controlled heating to give a very slow rate of temperature rise. The time required to complete a heating cycle from 0°C to 100°C was approximately two hours. The temperature could be held constant at any value for at least one minute. Readings were made at the appropriate temperature values during the heating cycle.

Transistors with sealed metal cases were immersed directly in the oil; others were wrapped tightly in aluminum foil to exclude the oil.

The initial attempts to heat the transistors in a transistor oven, (similar to the one described in the reference listed below[1]), proved unsuccessful. The temperature gradient

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1 - R. L. Riddle and M. P. Ristenblatt Transistor Physics and Circuits, Prentice-Hall 1958, P. 367.

between the oven body and the transistor case gave temperature errors as high as 5°C and this error varied widely with the oven temperature.

The use of a thermostatically controlled crystal oven was considered, however, as temperatures below room temperature could not be conveniently obtained this idea was abandoned.

E. 4 Temperature Measurement

The transistor case temperature was measured using a mercury bulb thermometer kept in close contact with the transistor case. The thermometer could be read to within ± 0.5°C. The slow rate of heating and the relatively long constant temperature time interval at each reading point ensured that the case and junction temperature were the same as the oil bath value.

A thermocouple was first used for temperature measurement, but proved unsatisfactory because the time required to balance the recorder made simultaneous voltage, current and temperature readings impossible.

E. 5 Resistances

All resistances used were laboratory decade resistance boxes. These resistance boxes are accurate to 1% of the resistance value.

E. 6 Circuits

The circuits for the various tests are all included in the main body of the report, at the appropriate places, and reproduction in this appendix was not considered necessary.

APPENDIX F

STABILIZATION NETWORK USING VOLTAGE FEEDBACK

F. 1 Introduction

A network using only voltage feedback, or a combination of voltage and current feedback, may be used to stabilize the operating point.

F. 2 Voltage Feedback Network

Refer to Figure 4.1, Page 18. Voltage feedback may be obtained from this circuit by connecting the resistance R_b directly to the collector and reducing the current feedback resistance R_e to zero. The resulting network is shown in Figure F.1.

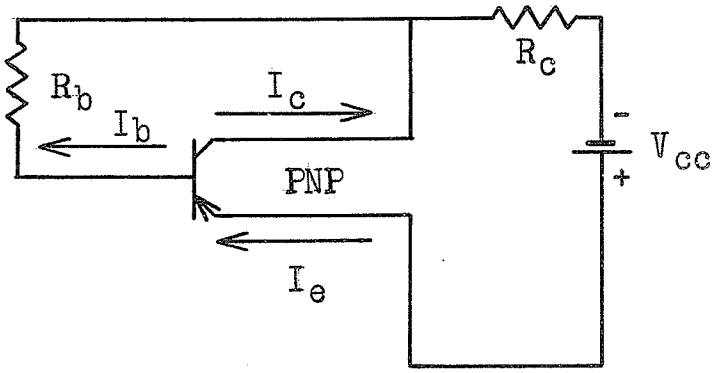

FIGURE F.1

VOLTAGE FEEDBACK NETWORK

Refer to Figure F.1. The following equation may be obtained by considering the voltages around the emitter-base

circuit:

$$V_{cc} = V_{eb} + I_bR_b + (I_b + I_c)R_c \qquad F.1$$

If V_{eb} is neglected, equation F.1 becomes:

$$V_{cc} = I_b(R_b + R_c) + I_cR_c \qquad F.2$$

If the value of I_b from equation 4.26, Page 29, is substituted for I_b in equation F.2 and the resulting equation solved for I_c the following equation is obtained:

$$I_c = \frac{R_c + R_b}{R_c + R_b(1-\alpha)} I_{co} + \frac{\alpha V_{cc}}{R_c + R_b(1-\alpha)} \qquad F.3$$

The derivative of I_c with respect to I_{co} of equation F.3 is:

$$S = \frac{dI_c}{dI_{co}} = \frac{R_c + R_b}{R_c + R_b(1-\alpha)} \qquad F.4$$

This voltage feedback stabilization network has the following disadvantages:

(1) there is no stabilization for change in V_{eb} (low temperature) as the emitter lead resistance is zero.

(2) stabilization for change in I_{co} (high temperature) is low (S becomes large) as R_c becomes small; e.g. R_c would be very small for a transformer coupled stage.

(3) R_b provides a negative feedback path for signal voltages; if this feedback is undesirable it must be by-passed to ground.

F. 3 Voltage and Current Feedback

Current feedback may be used to nullify the effect of change in V_{eb} by placing a current feedback resistance R_e in the emitter lead. A network using both voltage and current feedback is shown in Figure F.2.

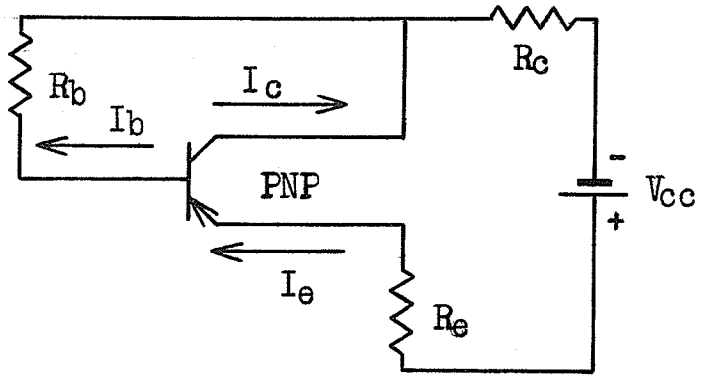

FIGURE F.2

VOLTAGE AND CURRENT FEEDBACK NETWORK

Refer to Figure F.2. The following equation may be obtained by considering the voltages around the emitter-base circuit:

$$V_{cc} = V_{eb} + I_eR_e + I_bR_b + (I_b + I_c)R_c \qquad F.5$$

If V_{eb} is neglected equation F.5 becomes:

$$V_{cc} = I_e R_e + I_b R_b + (I_b + I_c) R_c \qquad F.6$$

If the value of I_e from equation 4.25, Page 29, and the value of I_b from equation 4.26, Page 29, is substituted for I_e and I_b, respectively, in equation F.6 and the resulting equation solved for I_c the following equation is obtained:

$$I = \frac{R_e + R_c + R_b}{R_e + R_c + R_b(1-\alpha)} I_{co} + \frac{\alpha V_{cc}}{R_e + R_c + R_b(1-\alpha)} \qquad F.7$$

The derivative of I_c with respect to I_{co} of equation F.7 is:

$$S = \frac{dI_c}{dI_{co}} = \frac{R_e + R_c + R_b}{R_e + R_c + R_b(1-\alpha)} \qquad F.8$$

The resistance R_e improves the high temperature as well as the low temperature stabilization. The inclusion of R_e in the stability equation makes the value of S less dependent on R_c; R_c can be zero in equation F.8 and yet S will be less than the maximum value of $\frac{1}{1-\alpha}$ if R_e is not zero.

F. 4 Separate Bias and Stabilization Control

The addition of a resistance R_a, between the base and emitter terminals, permits separate control of the bias and stabilization. A network using voltage and current feed-

back, with separate bias and stabilization control, is shown in Figure F.3.

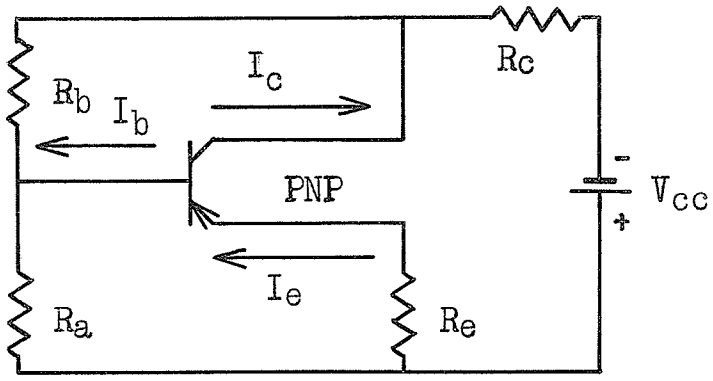

FIGURE F.3

NETWORK FOR SEPARATE BIAS AND STABILIZATION CONTROL

Refer to Figure F.3. If this network is solved for I_c (using a similar approach to the one used in Section 4.4) and the derivative of I_c with respect to I_{co} is taken the following equation is obtained:

$$S = \frac{dI_c}{dI_{co}} = \frac{(R_a + R_b + R_c)R_e + R_aR_c + R_aR_b}{(R_a + R_b + R_c)R_e + R_aR_c + R_aR_b(1-\alpha)} \qquad \text{F.10}$$

When the value of R_c in equations F.4, F.8 and F.10 equals zero these equations reduce to the following values:

$$\text{(Eq. F.4)} \qquad S = \frac{1}{1-\alpha} \qquad \text{F.11}$$

$$\text{(Eq. F.8)} \qquad S = \frac{R_e + R_b}{R_a + R_b(1-\alpha)} \qquad \text{F.12}$$

(Eq. F.10) $$S = \frac{R_aR_e + R_bR_e + R_aR_b}{R_aR_e + R_bR_e + R_aR_b(1-\alpha)} \qquad F.13$$

These stability equations are now identical with the stability equations developed in Chapter 4:

Equation F.11 = Equation 4.18, Page 26

Equation F.12 = Equation 4.16, Page 26

Equation F.13 = Equation 4.32, Page 30

BIBLIOGRAPHY

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BOOKS

1. Arguimbau, L. B. and Adler, R. B., Vacuum Tube Circuits and Transistors, Wiley 1956, p. 647
2. Carroll, J. M. et al, Transistor Circuits and Applications, McGraw-Hill 1957, p. 283
3. Coblenz, A. and Owens, H. L., Transistor Theory and Applications, McGraw-Hill 1955, p. 313
4. DeWitt, D. and Rossoff, A. L., Transistor Electronics, McGraw-Hill 1957, p. 381
5. Hunter, L. P. et al, Handbook of Semiconductor Electronics, McGraw-Hill 1956,
6. Hurley R. B. Junction Transistor Electronics, Wiley 1958, p. 473
7. Lin, H. C. and Barco, A. A., Temperature Effects in Circuits Using Junction Transistors, Transistors 1, RCA Laboratories 1956, p. 676
8. Lo, A. W. et al, Transistor Electronics, Prentice-Hall 1955, p. 520
9. Middlebrook, R. D., Junction Transistor Theory, Wiley 1957, p. 296
10. Riddle, R. L. and Ristenbatt, M. P., Transistor Physics and Circuits, Prentice-Hall 1958, p. 428
11. Shea, R. F. ed, Principles of Transistor Circuits, Wiley 1953, p. 533

12. Shea, R. F., Transistor Audio Amplifiers, Wiley 1957, p. 219

13. Shea, R. F. ed, Transistor Circuit Engineering, Wiley 1957, p. 468

14. Schaffner, J. S., Junction Transistor Applications, Advances in Electronics, Academic Press 1953, p. 420

SCIENTIFIC PAPERS

15. Ghandi, S. K., Bias Considerations in Transistor Circuit Design, IRE - PGCT, Vol. CT-4, pp. 194-202. Sept. 57

16. Lin, H. C., Thermal Stability of Junction Transistors and its effect on maximum power dissipation, IRE - PGCT, Vol. CT-4, pp. 202-210, Sept. 57

17. Moody, N. F., Junction Transistor Amplifiers: a note on stabilization of static operating conditions, DRB memo 40, Jan. 54

18. Mooers, H. T., Germanium Power Transistors, Honeywell Publication, Feb. 55

19. Mooers, H. T., Design Procedures for Power Transistors, Honeywell Publication, Feb. 56

20. Shea, R. F., Transistor Operation: Stabilization of operating points, Proc. IRE, Vol. 40, pp. 1435-1437, Nov. 52

21. Sher S. and Kwap T., Stabilizing Transistors Against Temperature Variations, Tele-Tech Vol. 14, pp. 74-76, Mar. 55