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TEMPERATURE COMPENSATION
OF ASTABLE MULTIVIBRATORS

Ira R. Marcus
Alan D. Smith

20 January 1964



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FOR THE COMMANDER:
Approved by



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ABSTRACT

A study was made to determine the limits to which the frequency of astable multivibrators could be stabilized against temperature and power-supply voltage variations so that they could be used as a time base in electric time fuzes and programmers.

The temperature range was -55° to $+75^{\circ}\text{C}$, and the voltage variation was ± 20 percent. The frequency was about 100 cps. Four different circuits are developed. One circuit yielded ± 0.06 percent frequency stability over the temperature and voltage range.

1. INTRODUCTION

In digital electronic timing and programming devices, the accuracy of the system depends upon the accuracy of the time base. The objective of this study was to determine if multivibrators could be compensated precisely enough for use as medium precision (1 to 0.1 percent) time bases for timers and programmers. Temperature and power-supply variations affect the frequency of uncompensated multivibrators. The temperature range under consideration is -55° to $+75^{\circ}\text{C}$, and the power-supply variation is ± 20 percent. The frequency of interest is about 100 cps.

Before analyzing the basic multivibrator, consider the simple RC circuit in figure 1. By differential equations we can show that

$$T = (RC) \ln \frac{V_a - V_{in}}{V_a - V_{tr}} \quad (1)$$

where T is the time for the capacitor to rise from V_{in} to V_{tr} ,

RC is the time constant of the RC circuit, which is assumed constant,

V_a is the voltage applied to the RC circuit,

V_{in} is the initial voltage on the capacitor,

and V_{tr} is the voltage at which the voltage detector triggers.

If the time T is to remain constant while V_a , V_{in} , and V_{tr} vary, then, the ratio $\frac{V_a - V_{in}}{V_a - V_{tr}}$ must remain constant. However,

$$\frac{V_a - V_{in}}{V_a - V_{tr}} = 1 + \frac{V_{tr} - V_{in}}{V_a - V_{tr}} \quad (2)$$

and thus, for T to remain constant while V_a , V_{in} , and V_{tr} vary, the ratio

$$F = \frac{V_{tr} - V_{in}}{V_a - V_{tr}} \quad (3)$$

must remain constant. Figure 1 displays two charging conditions for the capacitor. The ratios F for these conditions are

$$F_1 = \frac{W}{X} \quad \text{and} \quad F_2 = \frac{Y}{Z} \quad (4)$$

and the time T for both conditions are from equations (1, 2, 3, and 4)

$$T_1 = RC \ln [1+F_1] \quad \text{and} \quad T_2 = RC \ln [1+F_2] \quad (5)$$

If $F_1 = F_2$, then $T_1 = T_2$. It will be the objective of all the compensation methods in the following sections to keep F constant and equal to one. Thus the objective will be to keep

$$V_{tr} - V_{in} = V_a - V_{tr} \quad (6)$$

under all conditions.

2. BASIC UNCOMPENSATED MULTIVIBRATOR

We now examine the uncompensated multivibrator (fig. 2). Figure 3 shows the waveforms at various points. Reference 1 contains a complete description of the circuit's operation. A brief description follows:

- (a) If Q_2 had just turned OFF, then V_{C2} rises from V_{S2} to B through R_3C_2 (time constant) charging path.
- (b) When Q_2 is OFF, V_{BE2} rises from $-(B - V_{S1} - V_{B2})$ through R_1C_1 toward B. V_{BE2} equals V_{B2} when Q_2 is ON.
- (c) When V_{BE2} reaches Q_2 's forward ON voltage V_{B2} , then Q_2 turns ON.
- (d) When Q_2 turns ON, V_{BE1} drops to $-(B - V_{S2} - V_{B1})$, and Q_1 is cut off. V_{BE1} equals V_{B1} when Q_1 is ON.
- (e) With Q_1 OFF, V_{C1} rises to B from V_{S1} through R_4C_1 .
- (f) While Q_1 is OFF, V_{BE1} climbs from $-(B - V_{S2} - V_{B1})$ through R_2C_2 toward B.
- (g) When V_{BE1} reaches Q_1 's forward ON voltage, V_{B1} , Q_1 turns ON.

(h) When Q_1 turns on, Q_2 is cut off, since V_{BE2} drops to $-(B - V_{S1} - V_{B2})$, and the cycle has been completed.

From equations (1 and 2) the period P is

$$P = T_1 + T_2 = R_1 C_1 \ln \left[1 + \frac{V_{B2} + (B - V_{S1} - V_{B2})}{B - V_{B2}} \right] + R_2 C_2 \ln \left[1 + \frac{V_{B1} + (B - V_{S2} - V_{B1})}{B - V_{B1}} \right] \quad (7)$$

Now if Q_1 and Q_2 are similar transistors so that

$$V_{S1} = V_{S2} = V_S \quad \text{and} \quad V_{B1} = V_{B2} = V_B$$

then we can write

$$P = (R_1 C_1 + R_2 C_2) \ln \left[1 + \frac{B - V_S}{B - V_B} \right] \quad (8)$$

If $B \gg V_S$

$$P = (R_1 C_1 + R_2 C_2) \ln \left[1 + \frac{B}{B - V_B} \right] \quad (9)$$

and if B is also much greater than V_B then

$$P = (R_1 C_1 + R_2 C_2) \ln 2 = 0.69 [R_1 C_1 + R_2 C_2] \quad (10)$$

Good design requires that

(a) R_1 and R_2 are low enough to insure that the transistors will saturate when ON.

(b) $R_4 C_1 \ll R_2 C_2$ and $R_3 C_2 \ll R_1 C_1$ so that collector voltages will quickly recharge to the supply potential during OFF periods.

(c) The transistor switching times should be sufficiently low so that they do not appreciably influence the frequency.

3. CIRCUIT ANALYSIS FOR VOLTAGE AND TEMPERATURE VARIATIONS

V_S and V_B are changed by temperature and power-supply variations and are not so small (fig. 4) compared to B , that they can be neglected in a precision oscillator. They must be compensated for. As may be noticed we have two power supplies A and B. Assume a symmetric circuit.

$$(R_1 = R_2, R_3 = R_4, C_1 = C_2, Q_1 = Q_2).$$

Equation (8) now becomes

$$P = 2R_1 C_1 \ln \left(1 + \frac{A - V_S}{B - V_B} \right) \quad (11)$$

For the period to be independent of power-supply variations and temperature variations, the ratio $\frac{A - V_S}{B - V_B}$ must be constant, and $R_1 C_1$

must be constant. Assume R_1 , R_2 , C_1 , and C_2 are not temperature dependent. The ratio $\frac{A - V_S}{B - V_B}$ is close to 1. We will provide compen

sation circuits to make this ratio equal to one. We determine to keep $B - V_B = A - V_S$ under all conditions. V_B is an order of magnitude greater than V_S and is much more temperature dependent. Therefore, the principal problem is to keep $A = B - V_B$ when $V_S \approx 0$.

4. SINGLE-DIODE COMPENSATION CIRCUIT

Figure 5 shows the circuit of an uncompensated multivibrator. The coupling capacitors and the base resistors have small temperature coefficients. Tests indicate that over the temperature range considered, they contribute about 0.1 percent variation in period. The circuit at -6-v supply voltage has a linear period-versus-temperature curve. As the temperature increases, the period decreases. V_B becomes smaller with increasing temperature, and thus, the OFF transistor is triggered on earlier. The variation of period with temperature is +2.5 percent of the center value.

The period variation with voltage is greatest at -55°C, where the value of V_B is the largest, and where the equation $A = B - V_B$ is violated to a greater degree. However, -6-v \pm 20 percent caused a maximum variation of ± 1.5 percent in period at -55°C. Thus, controlling the supply voltage to ± 1 percent should cause variations in period less than ± 0.1 percent. Previous work in voltage regulators indicate that simple regulators can be designed to this specification.

Figure 6 displays the same circuit with a single-diode compensation circuit. Voltage A is now voltage B minus the voltage drop across the silicon diode, and the ratio in equation (11) is

$$\frac{B - V_D - V_S}{B - V_B}$$

. The 530 ohm resistor value was determined by adjustment

until the voltage across the diode V_D equalled V_B at room temperature and at -6-v supply voltage. The period variation with temperature is now ± 1 percent, about 2 1/2 times smaller than the uncompensated circuit. The variation with voltage is somewhat better. Better voltage results were not gotten because V_D is affected more

by changes in supply voltage than is V_B , since the current through the diode varies with supply voltage. It may be noted that the resulting compensated curve is still linear, and further compensation can be accomplished with linear elements in the RC circuits.

5. SINGLE-TRANSISTOR COMPENSATION CIRCUIT

Compensation using the base-to-emitter junction of a complementary transistor was examined. Figure 7 shows the properties of the circuit before compensation. Figure 8 shows the same circuit after compensation. Improvement by a factor of 3 is shown. The overall error after compensation is about the same as with the diode. However, this method requires less power since the load resistor is 10 k with the transistor and was 530 ohms with the diode. Linearity is again evident with the transistor. Voltage compensation is about the same as with the diode. Both compensated and uncompensated circuits used small temperature-coefficient timing capacitors and resistors, which contributed less than 0.1-percent change over the temperature range.

6. DOUBLE-DIODE COMPENSATION CIRCUIT

Figure 9 shows the properties of a multivibrator similar to the one in figure 5 but made with different components. Figure 10 shows the result of double germanium-diode compensation added to this circuit. Here the ratio that must be kept constant for period stability is $\frac{B-2V_D-V_S}{B-V_B}$. The curve shows that diodes over compensate and reverse the slope. This circuit gives a positive slope. This is because the two diodes have a negative coefficient. The 800-ohm resistor was determined the same way the 530-ohm resistor in figure 6 was.

7. TRIM COMPENSATION OF THE DOUBLE-DIODE COMPENSATION CIRCUIT

Since the circuit in figure 10 had a positive slope causing about a 1.1-percent change in period and was linear, the next attempt at compensation was in the RC portion. Here the zero temperature-coefficient capacitors were replaced by polystyrene capacitors. These capacitors have nearly linear negative coefficients of about 100 ppm per degree centigrade. Figure 11 shows that compensation to ± 0.14 percent is achieved with these capacitors at 6 v. Thus compensation to 0.2 percent can be achieved using double germanium-diode compensation, polystyrene capacitors, and simple voltage regulation at 6 v.

8. SECOND-ORDER COMPENSATION CIRCUIT

The three circuits described above are first-order attempts at compensation. A circuit intended to compensate for second-order effects will now be developed.

Before examining the fully developed compensated circuit, consider the circuit in figure 12. Here Q_3 , Q_4 , and Q_5 are added for compensation. If the frequency is to remain invariant with temperature and voltage variations, the following two ratios from equations (3, 4) must remain constant

$$K_1 = \frac{B-V_{B5}-V_{S2}}{B-V_{S4}-V_{B1}} \quad \text{at the base of } Q_1 \quad (12)$$

and

$$K_2 = \frac{B-V_{B5}-V_{S1}}{B-V_{S3}-V_{B2}} \quad \text{at the base of } Q_2 \quad (13)$$

If

$$V_{S4} = V_{S2}, \quad V_{B1} = V_{B5}$$

$$V_{B2} = V_{B5}, \quad V_{S3} = V_{S1}$$

then both ratios would be constant, and the frequency would be stable with temperature and power-supply voltage variations. These conditions can be closely approximated if all five transistors have the same base-to-emitter and saturation voltages. Since V_S and V_B depend on operating points, and the operating points depend on base resistors and collector resistors, all the resistors in the circuit must be equal. This is because R_2 and R_3 are base resistors of Q_1 and Q_2 and at the same time are collector resistors of Q_3 and Q_4 . Similarly R_1 and R_4 are collector resistors of Q_1 and Q_2 and are also base resistors for Q_5 . The circuit is now compensated for temperature and power-supply voltage variations. However, due to the fact that the resistances are equal, it will no longer oscillate. This is because reliable operation requires the time constants $R_1 C_1 \ll R_3 C_2$ and $R_4 C_2 \ll R_2 C_1$. Since $R_1 = R_3$ and $R_2 = R_4$ this condition cannot be satisfied.

Figure 13 shows the compensated circuit modified so that oscillation can take place. Transistors Q_6 and Q_7 are used to charge capacitors C_2 and C_1 quickly, compared to the time constants of $R_2 C_1$ and $R_3 C_2$. This is accomplished by Q_6 conducting and charging C_2 when Q_1 is conducting, and Q_7 conducting and charging C_1 when Q_2 is conducting. R_{10} and R_{11} are much smaller than R_1 and R_4 . When both capacitors are being charged by this method V_{S6} and V_{S7} vanish since the charging currents through them go to zero. Diodes $D1$ and $D3$ are used to isolate R_1 and R_4 from C_1 and C_2 .

If the diode $D1$ is not included, the voltage at the collector of Q_1 would rise from V_{S1} to $B-V_{B5}$ when Q_1 is turning OFF, according to the time constant $R_1 C_1$. Q_2 would be turning ON and would be at

V_{S2} . However, Q_6 would be turned on and would cause the collector current of Q_2 to rise, which would in turn greatly increase V_{S2} . V_{S4} would no longer compensate V_{S2} . Diode $D1$ allows the collector of Q_1 to go from V_{S1} to $B-V_{B5}$ very rapidly when Q_1 is turning off, since C_1 is charged by Q_7 . Q_6 does not turn on when Q_1 is turned off, and, therefore, V_{S2} can be compensated by V_{S4} . Diode D_3 performs a similar function for Q_2 . The collector wave forms are now true square waves. To compensate for V_{D1} and V_{D3} , diodes D_2 and D_4 are added.

The voltage change at the base of Q_1 is found as follows. While Q_1 is conducting, one side of C_2 is at V_{B1} . The diode side charges up to $B-V_{B8}$. When Q_2 is turned on, its collector drops to V_{S2} , but the diode side of C_2 falls to only $V_{D3} + V_{S2}$. The voltage change at V_{BE1} is equal to the voltage change at the diode side of D_3 and is therefore $(B-V_{B8}) - (V_{D3} + V_{S2})$, as shown in figure 13.

The period of this oscillator is

$$P = R_3 C_2 \ln \left(1 + \frac{B-V_{B8} - V_{D3} - V_{S2}}{B-V_{B1} - V_{D4} - V_{S4}} \right) + R_2 C_1 \ln \left(1 + \frac{B-V_{B8} - V_{D1} - V_{S1}}{B-V_{B2} - V_{D2} - V_{S3}} \right) \quad (14)$$

For voltage and temperature compensation to occur, the following parameters must be matched:

$$\begin{array}{ccc} V_{S2} \text{ and } V_{S4} & V_{B8} \text{ and } V_{B1} & V_{D3} \text{ and } V_{D4} \\ V_{S1} \text{ and } V_{S3} & V_{B8} \text{ and } V_{B2} & V_{D1} \text{ and } V_{D2} \end{array}$$

and $R_2 C_1$ and $R_3 C_2$ are temperature compensated.

Thus transistors Q_1 , Q_2 , Q_3 , Q_4 , and Q_8 must have their V_B and V_S parameters matched.

Figure 14 shows the performance of the compensated circuit.

Figure 15 shows this same circuit with a 6-v regulator and the substitution of a 100-k, 100 ppm/°C resistor for one of the two 100-k, 0 ppm/°C resistors in the timing networks. The overall performance of the circuit is ± 0.06 percent from -55° to $+75^\circ$ C and from 12 v to 18 v. The unadjusted circuit at 6 v (fig. 14) changed its period ± 0.3 percent over the temperature range. This is because the transistors were not perfectly complementary. The PNP and the NPN transistors used in figures 14 and 15 were matched by specification sheet only and were not individually matched.

We now examine this circuit theoretically to determine its frequency versus temperature behavior when the transistors and diodes are not exactly matched.

Figure 16 is a schematic of the test circuit used to determine the temperature characteristics of V_B and V_S . Figures 17 through 20 show that V_B and V_S are basically linear in the temperature range of -55°C to $+75^{\circ}\text{C}$. Similarly, figure 21 shows the temperature properties of a typical diode. For a worst-case analysis, equation (14) can be written

$$P = R_3 C_2 \ln M + R_2 C_1 \ln N \quad (15)$$

Since the $\ln M$ and the $\ln N$ contain similar terms, equation (15) can be written

$$P = (R_3 C_2 + R_2 C_1) \ln M \quad (16)$$

Figure 22 is a worst-case plot of the $\ln M$. At each value of B (5, 7, and 10 v), a minimum and a maximum value of $\ln M$ is plotted as a function of temperature. This is accomplished by using the graphical data that describes the temperature properties of the variables which determine the $\ln M$.

The measured and plotted data for each variable is modified by drawing a worst-case curve parallel to and above the upper measured curve and another worst-case curve parallel to and below the lower measured curve. These two worst-case curves for each variable increase the maximum value of the variable at each temperature and decrease the minimum value of the variable at each temperature. The purpose of the worst-case curves is to make up for the small number of samples measured. The worst-case curves are parallel to the measured data curves and are separated by the maximum difference at any one temperature between the upper and lower measured curves.

The worst-case values of the variables were now used to plot the $\ln M$. The upper three curves in figure 22 were determined by using worst-case values of the variables which would maximize the $\ln M$. The lower three curves in figure 22 were determined by using the worst-case values of the variables which would minimize $\ln M$.

From equation (16), the period P is proportional to $\ln M$. All the curves in figure 22 are linear. This is because $\ln M$ does not vary greatly from 2.0. It is now clear why the prototype circuit displays linear temperature curves in figure 14 and why trim compensation to decrease period variations with temperature can be achieved with linear temperature coefficient resistors or capacitors or both. It is expected that a smaller amount of trim compensation will be required with transistors and diodes which are more closely matched.

9. SUMMARY AND CONCLUSIONS

The basic transistor multivibrator circuit can be temperature compensated by additional circuitry. The amount of additional

circuitry is proportional to the degree of compensation required. Additional trimming compensation is easily accomplished by resistors and/or capacitors with linear temperature coefficients. Single-diode or single-transistor circuit compensation yields ± 1 -percent period stability if used with a simple voltage supply regulator. Additional stability can be gotten by further trimming compensation with linear temperature-coefficient resistors or capacitors. Double-diode circuit compensation yields $\pm 1/2$ -percent period stability if used with a simple voltage supply regulator. Additional stability can be achieved by further trimming compensation with negative temperature-coefficient resistors or capacitors. This is less flexible than the first two types of compensation due to the limited number of components with negative coefficients. The breadboard of this prototype was stable to ± 0.10 percent. The second-order temperature compensation circuit yields ± 0.25 -percent stability if used with a simple voltage regulator. Further trimming compensation and supply voltage regulation yields ± 0.06 -percent stability.

In all the above compensation circuits, greatest stability was exhibited at the highest supply voltage. This is because the higher supply voltage swamps out the other terms and makes them less significant. Unfortunately the maximum value of the supply voltage that can be used is limited by the reverse breakdown characteristics of V_B of the transistor. At this time, 7 v is the highest available value of the reverse voltage which can be applied to the base-to-emitter junction.

In all the above circuits the RC portions were separately matched so that they introduced less than 0.1-percent error. The present state of RC components allows this to be easily accomplished.

It, therefore, appears that the multivibrator does have a place in the medium precision, low-frequency oscillator class.

10. RECOMMENDATIONS

Additional simpler compensation circuitry should be designed. Specifically, the second-order compensation circuit should be further examined. It is believed that Q_3 and Q_4 and R_5 and R_7 can be omitted. This can be accomplished by increasing R_1 and R_4 . This would reduce V_S . If V_S is small compared to the supply voltage, it need not be compensated for. (At the present time, the supply voltage is 6 v, and V_S is 0.05 v.) If V_S is very small, then all four diodes may also be eliminated. In addition, the effect of removing Q_5 and R_6 and connecting R_1 and R_4 to the base of Q_B should be studied.

11. REFERENCE

(1) Richard B. Hurley, "Transistor Logic Circuits," John Wiley and Sons, Inc., New York, 1961, pp 331, 333.

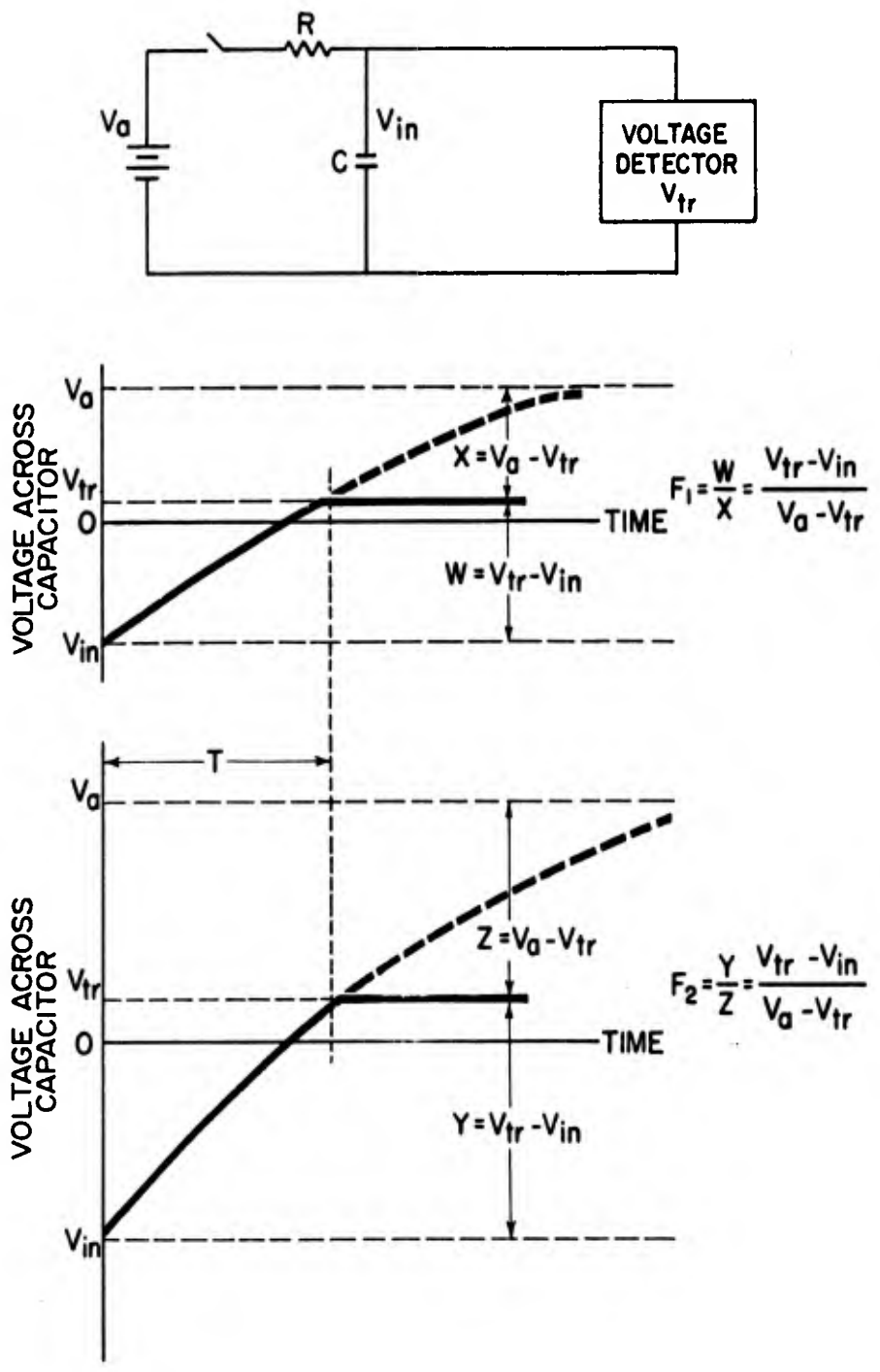


Figure 1. RC circuit and charging curves.

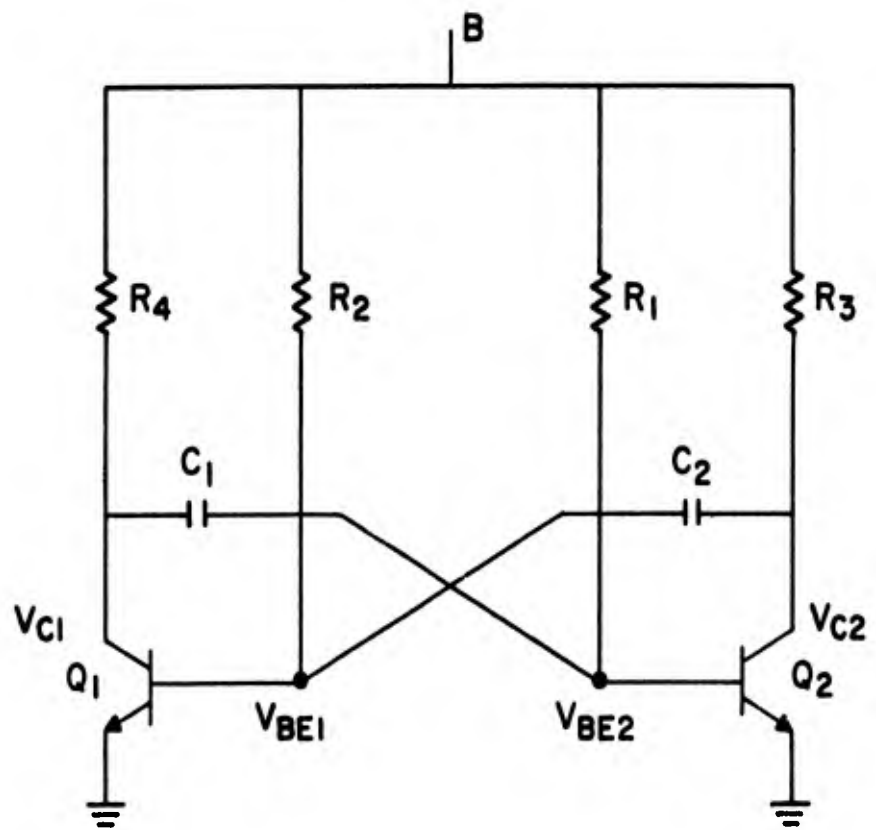


Figure 2. Astable multivibrator.

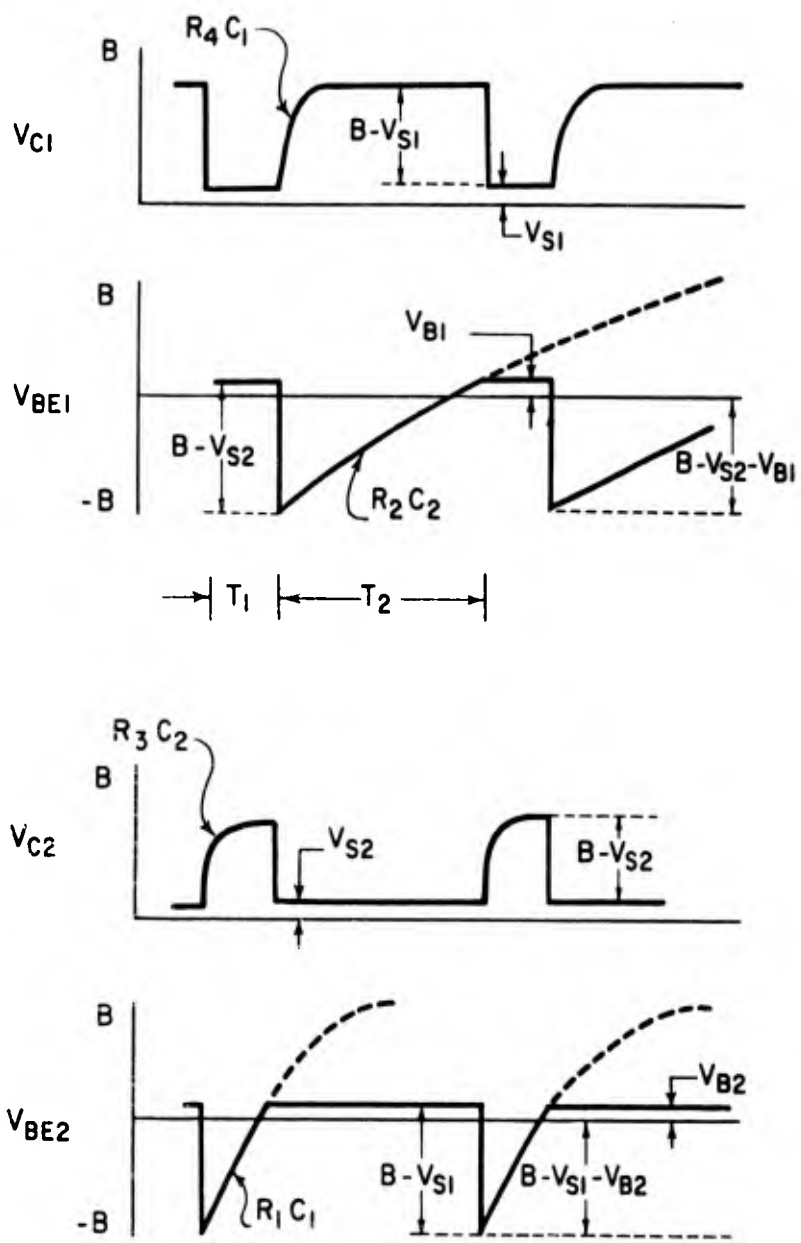


Figure 3. Multivibrator waveforms.

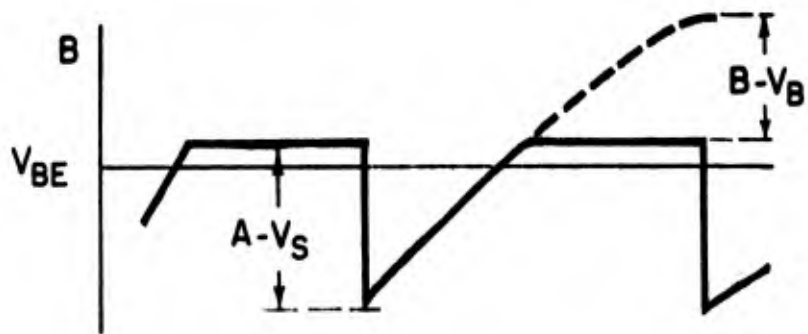
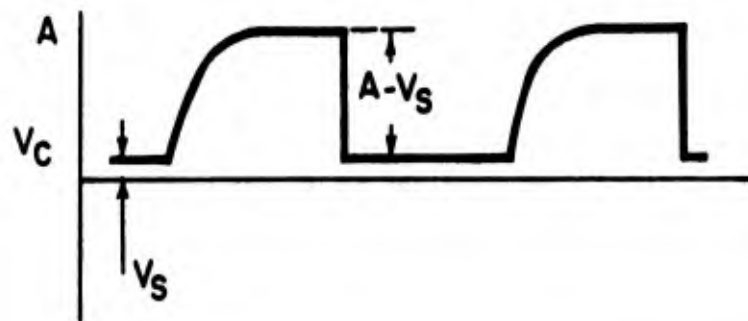
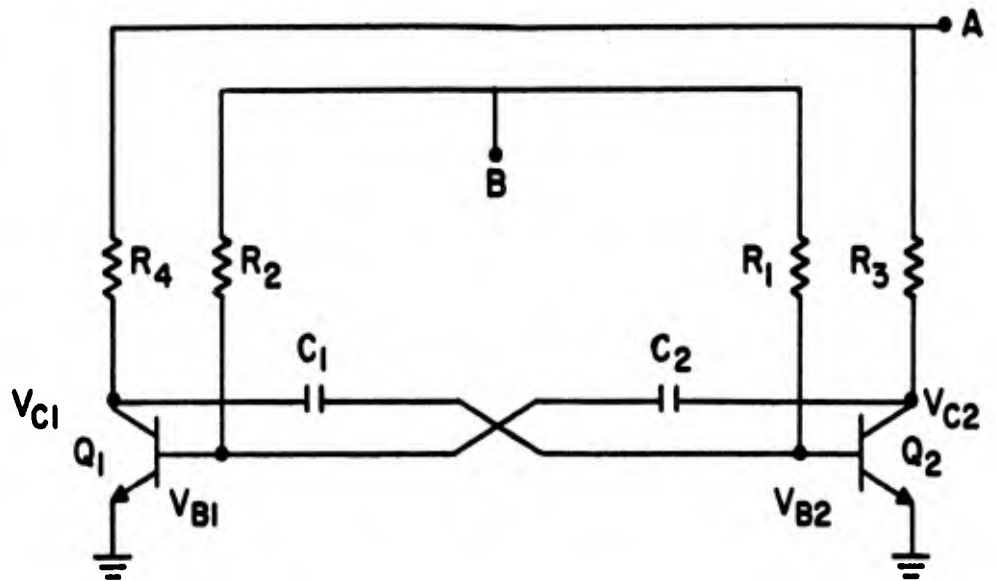


Figure 4. Dual voltage power supply multivibrator with waveforms.

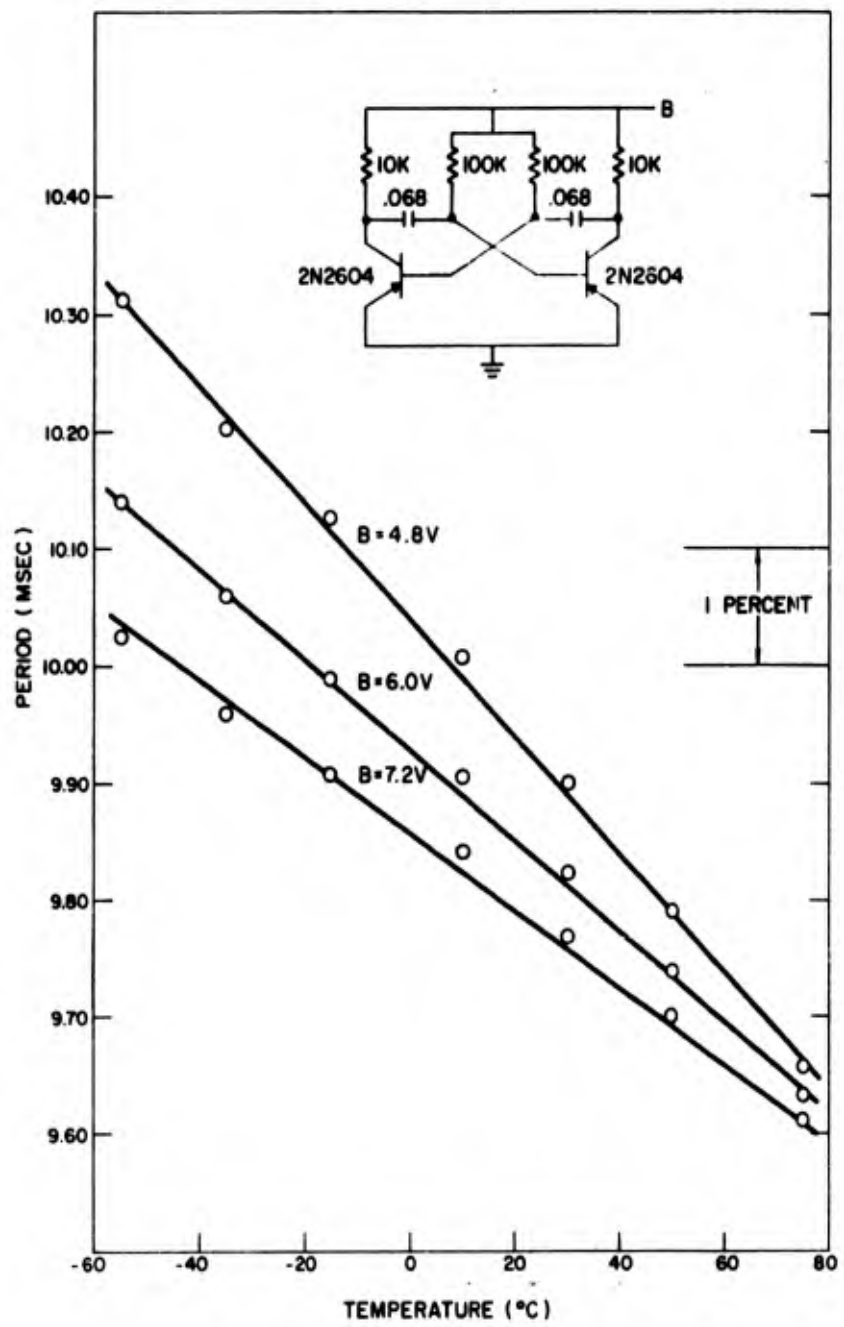


Figure 5. Uncompensated multivibrator ia and temperature properties.

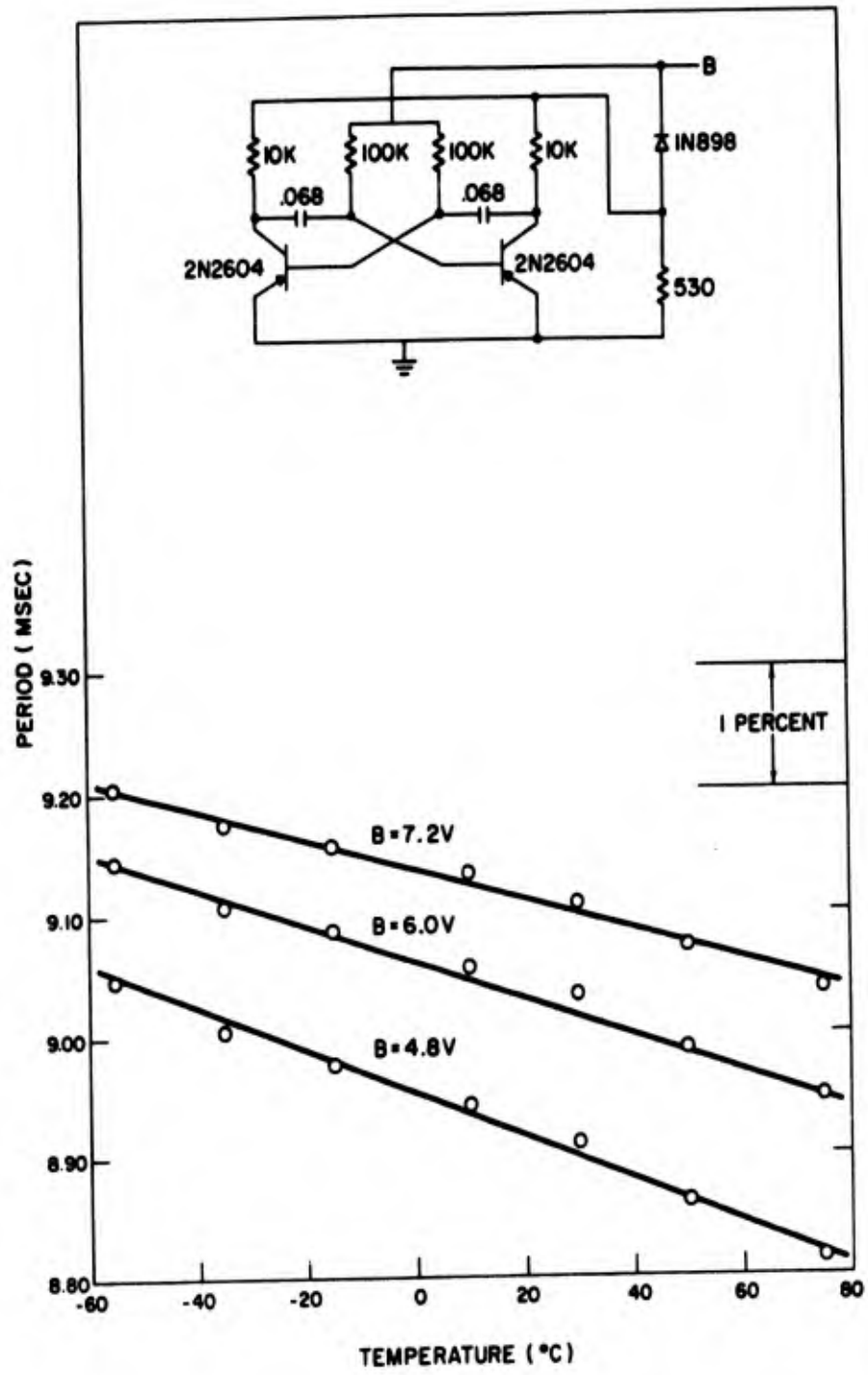


Figure 6. Multivibrator 1a with single-diode compensation circuit.

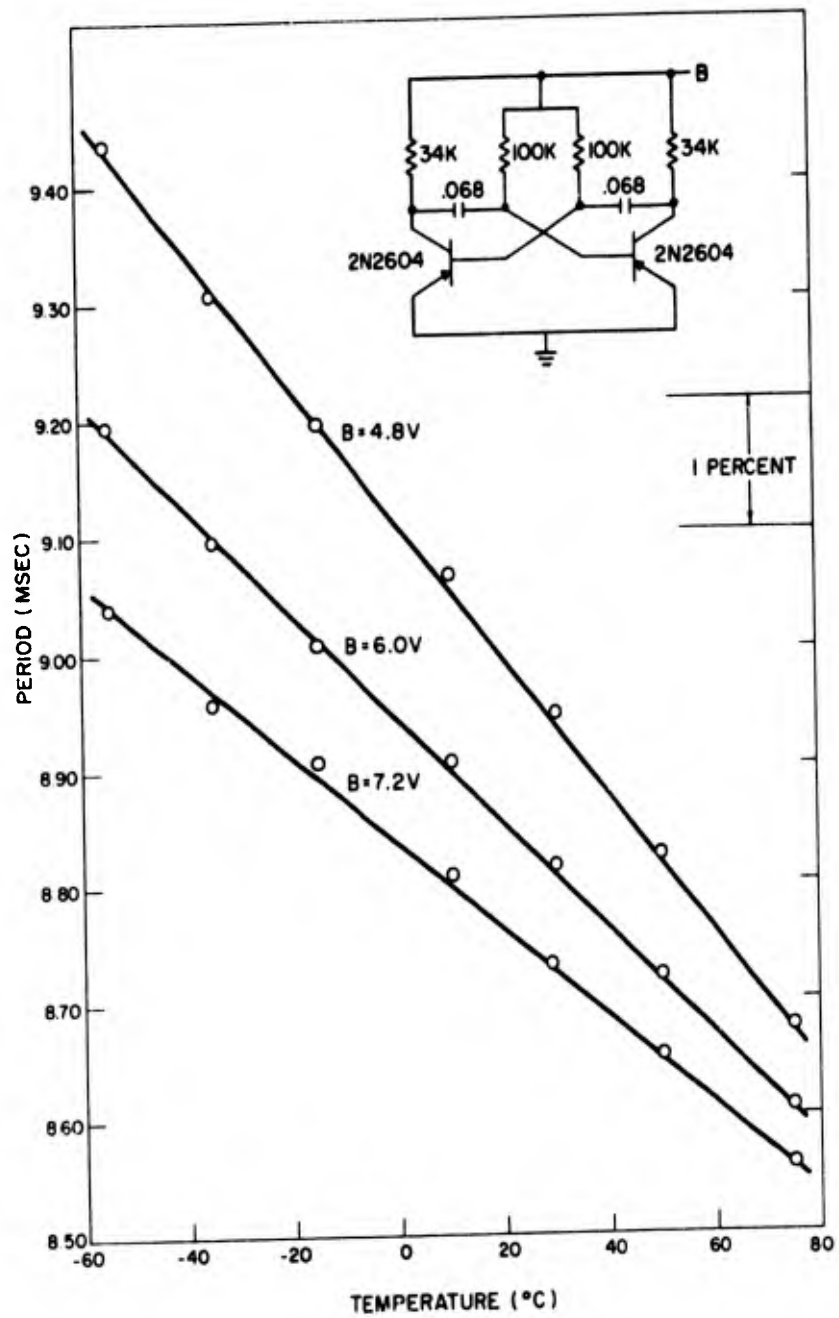


Figure 7. Uncompensated multivibrator 2.

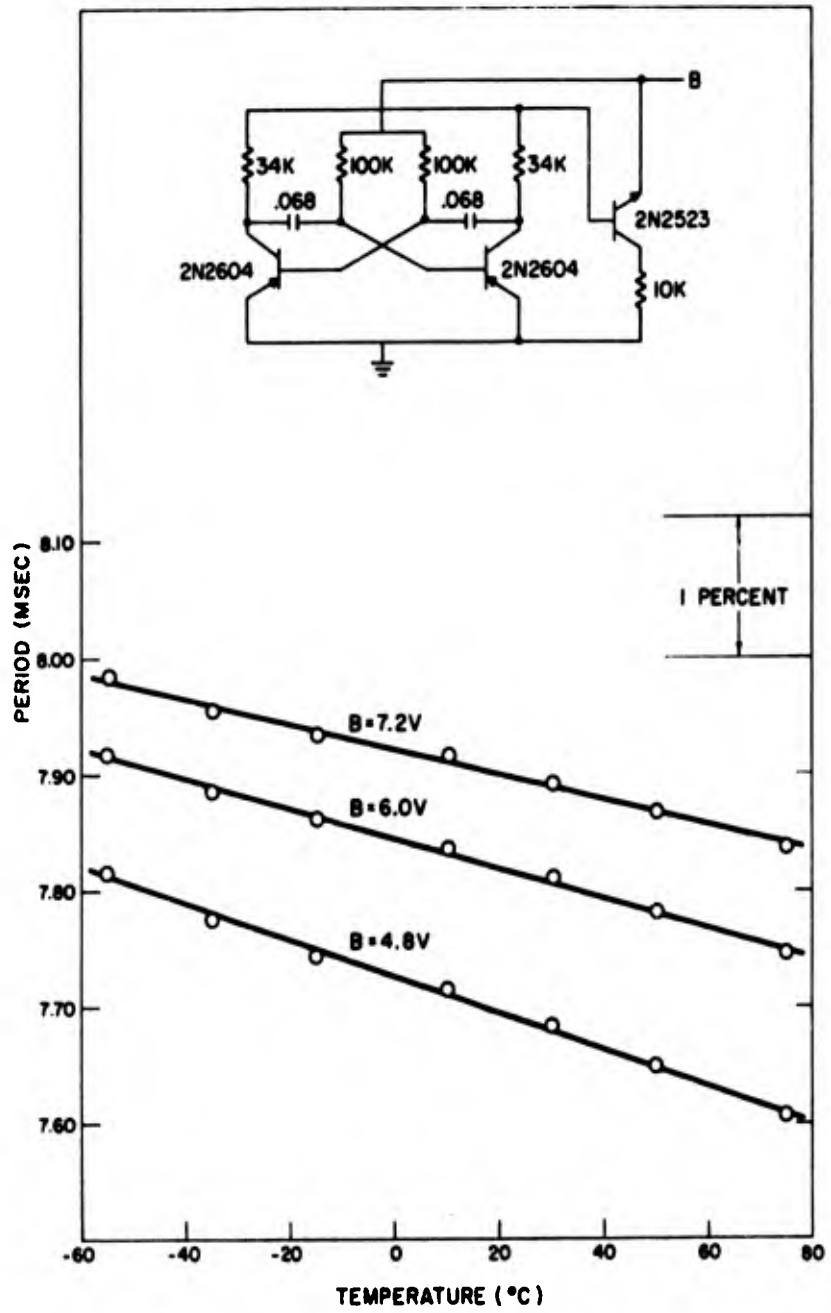


Figure 8. Multivibrator 2 with single-transistor compensation circuit.

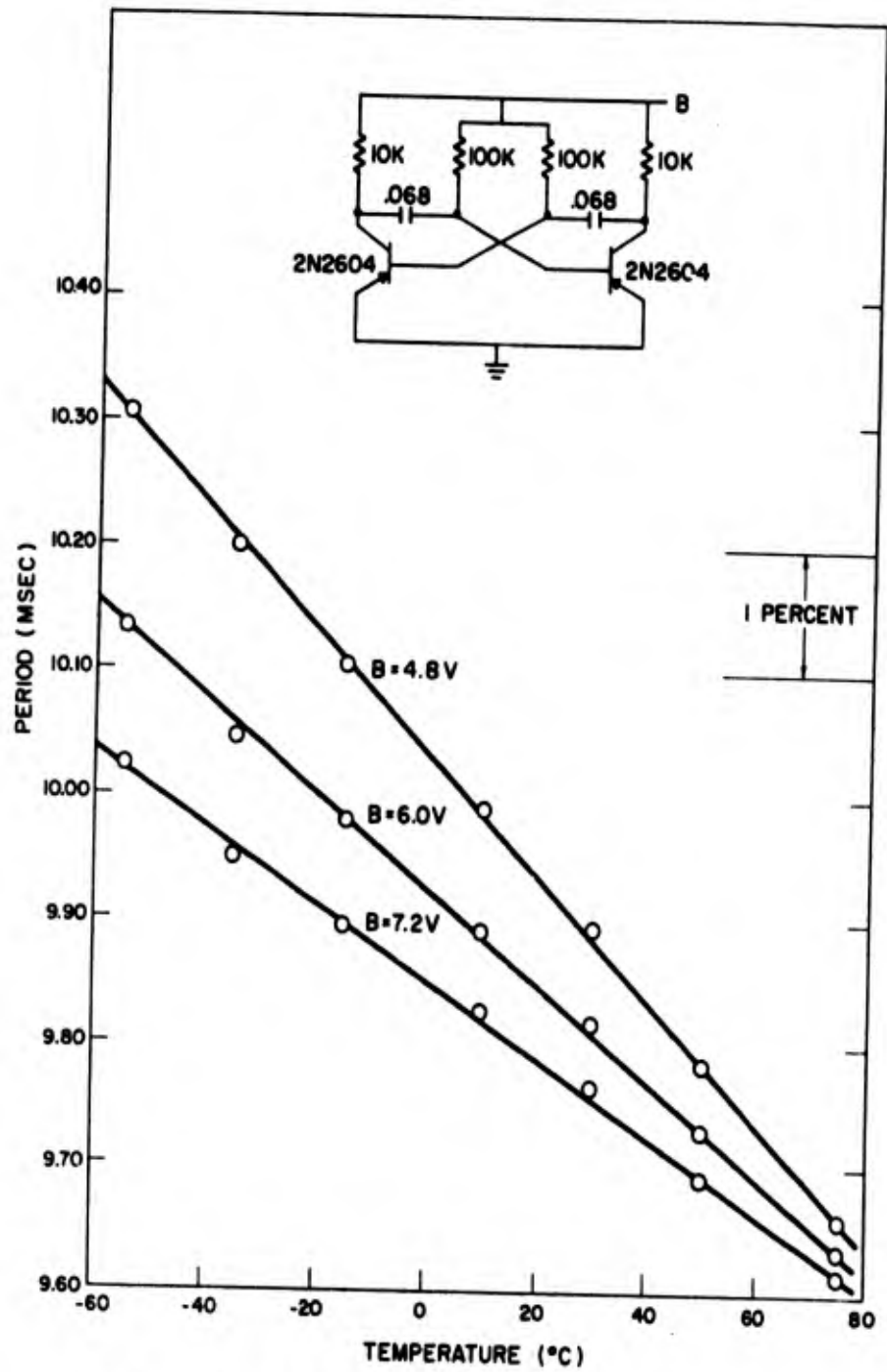


Figure 9. Uncompensated multivibrator 1b.

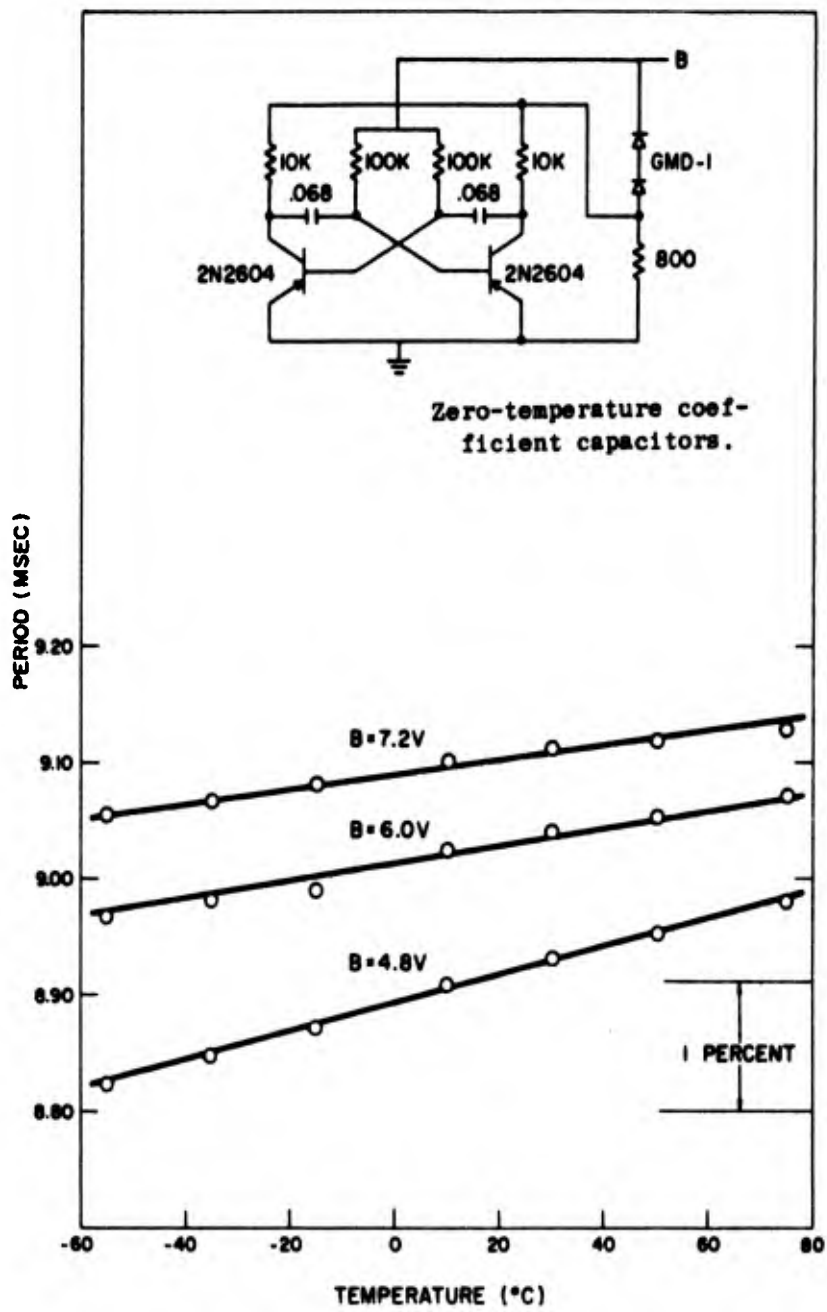


Figure 10. Multivibrator 1b with double-diode compensation circuit.

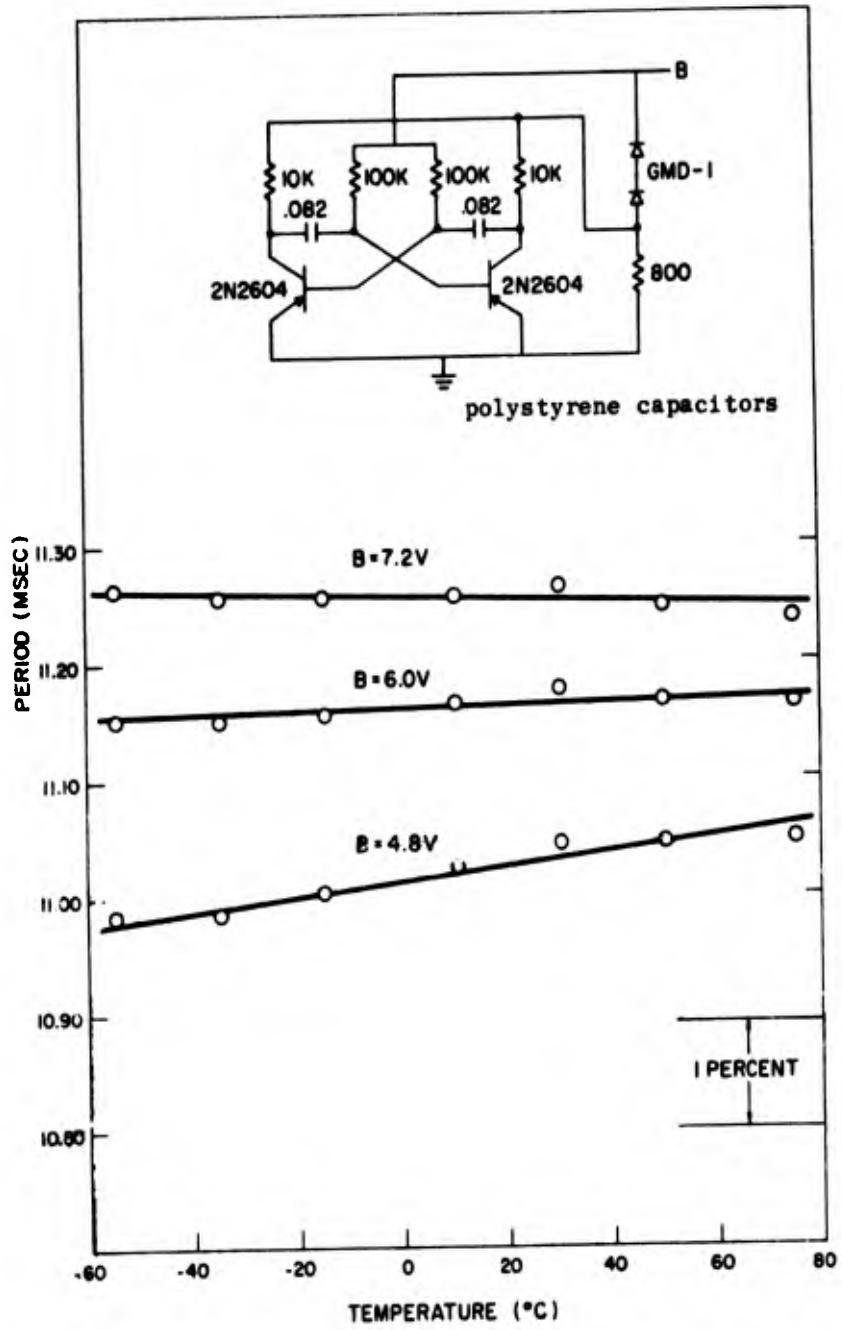


Figure 11. Trim compensation of double-diode compensated circuit.

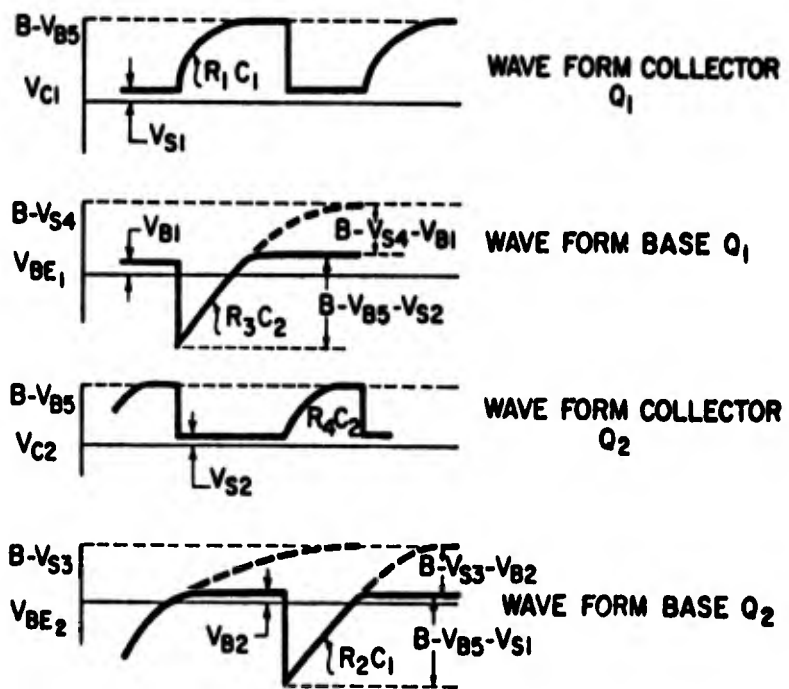
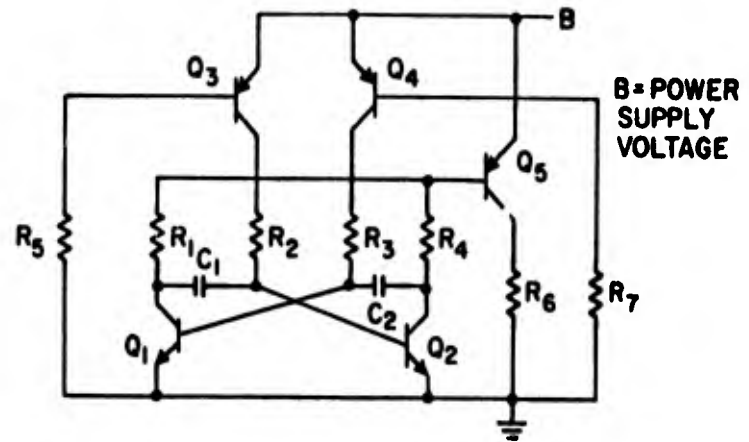


Figure 12. Ideal second-order compensated multivibrator circuit and waveforms.

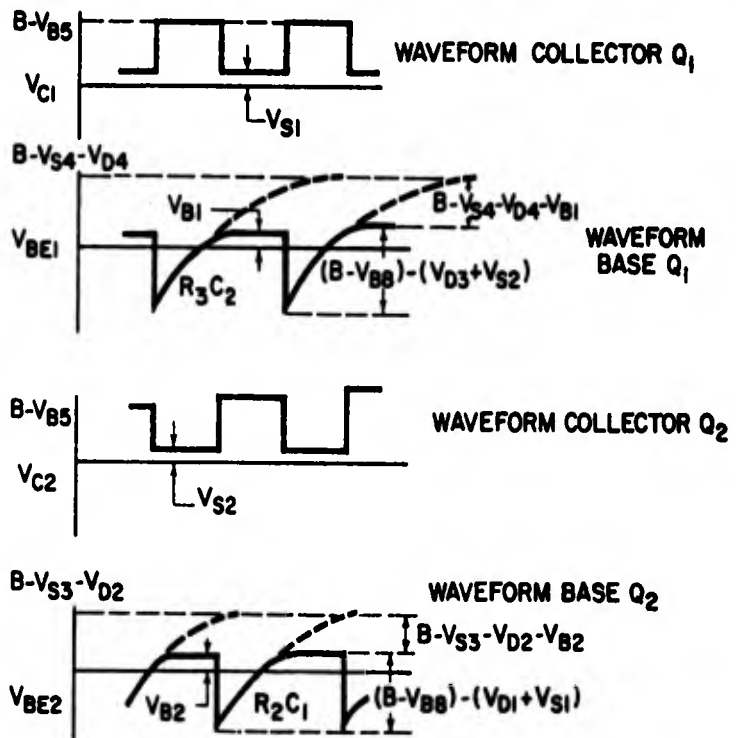
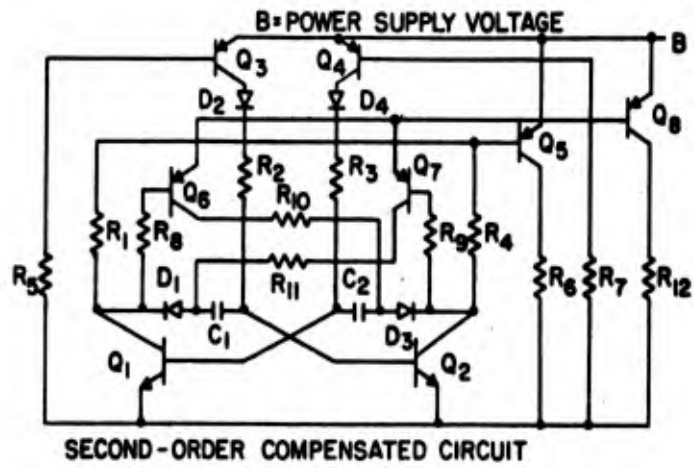


Figure 13. Operating second-order compensated multi-vibrator circuit and waveforms.

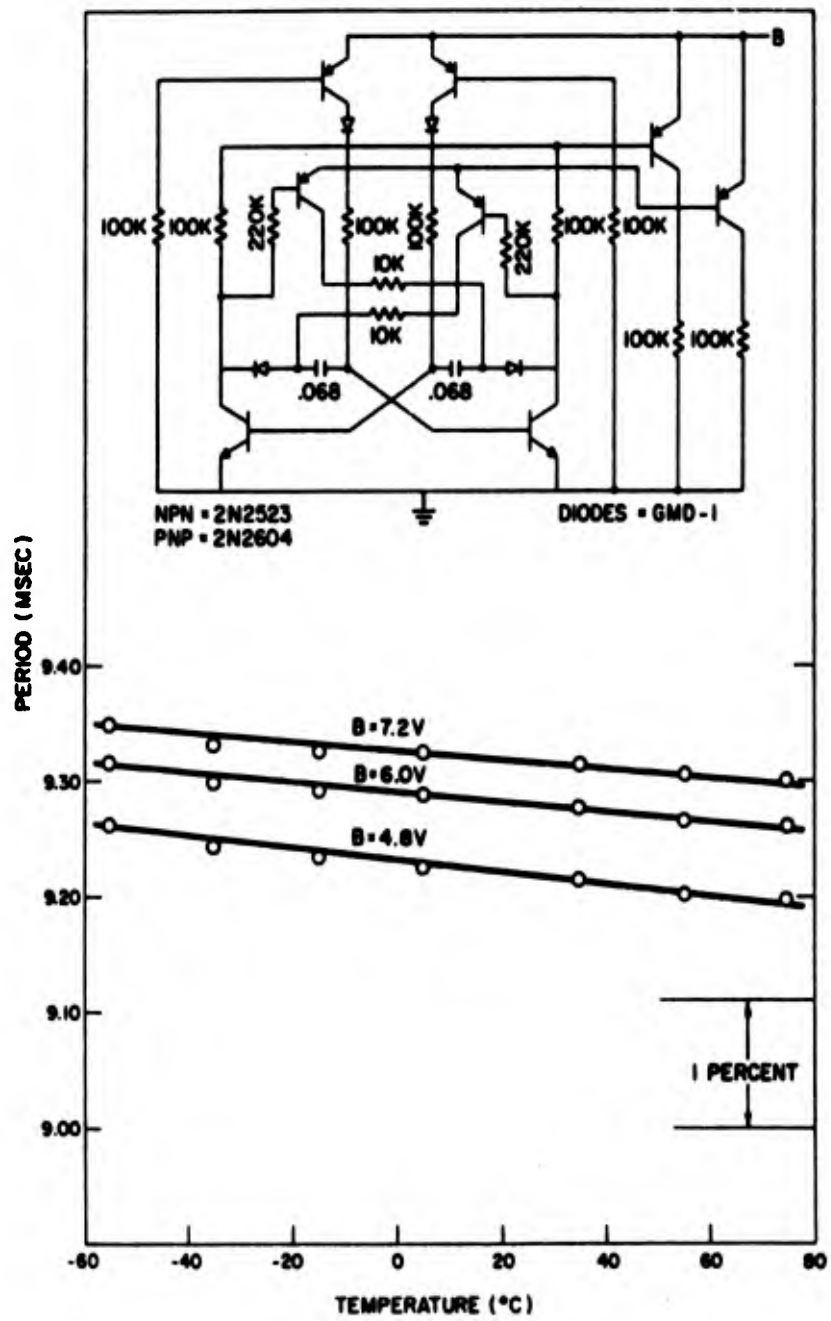


Figure 14. Operating characteristics of second-order compensated circuit.

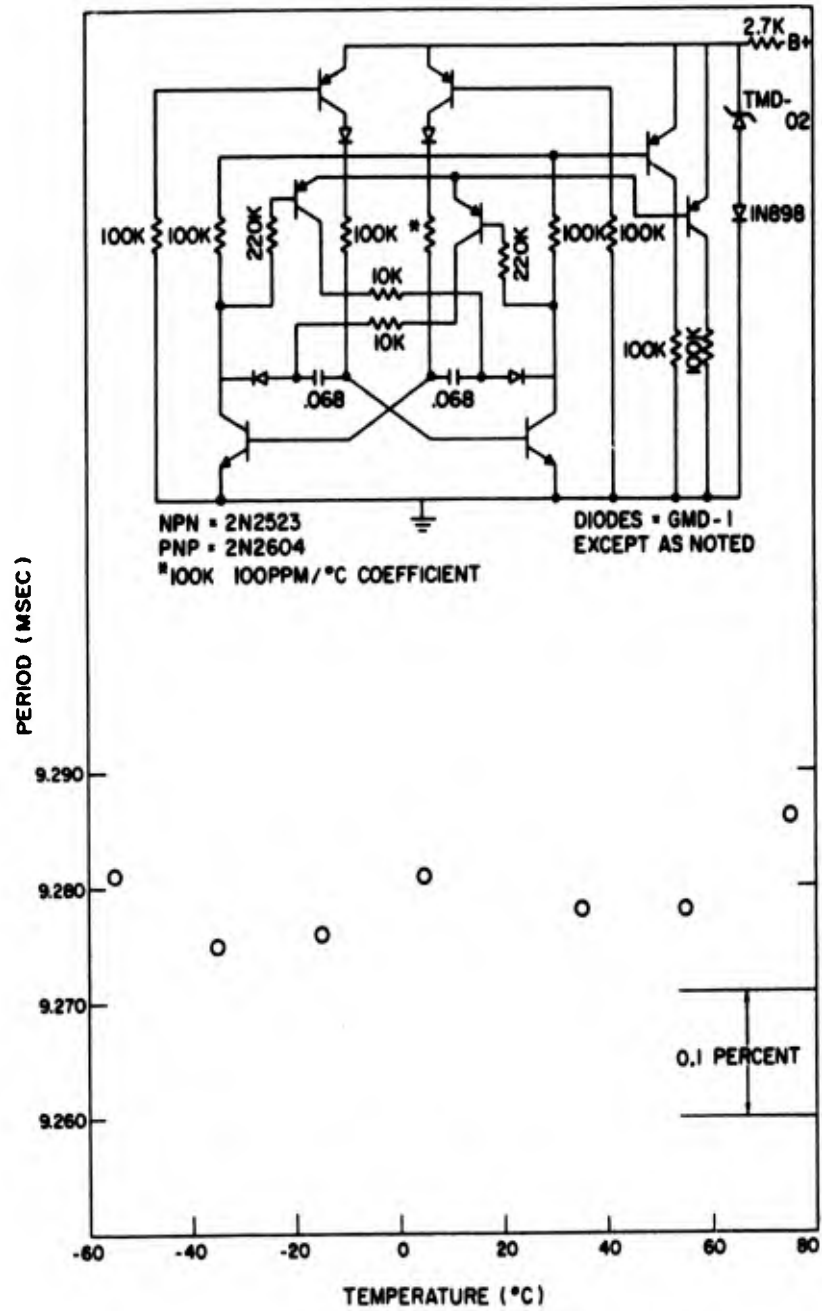


Figure 15. Operating characteristics of trim-compensated second-order compensated circuit. The period is constant to 0.0002 ms with power supply variations from 12 to 18 v.

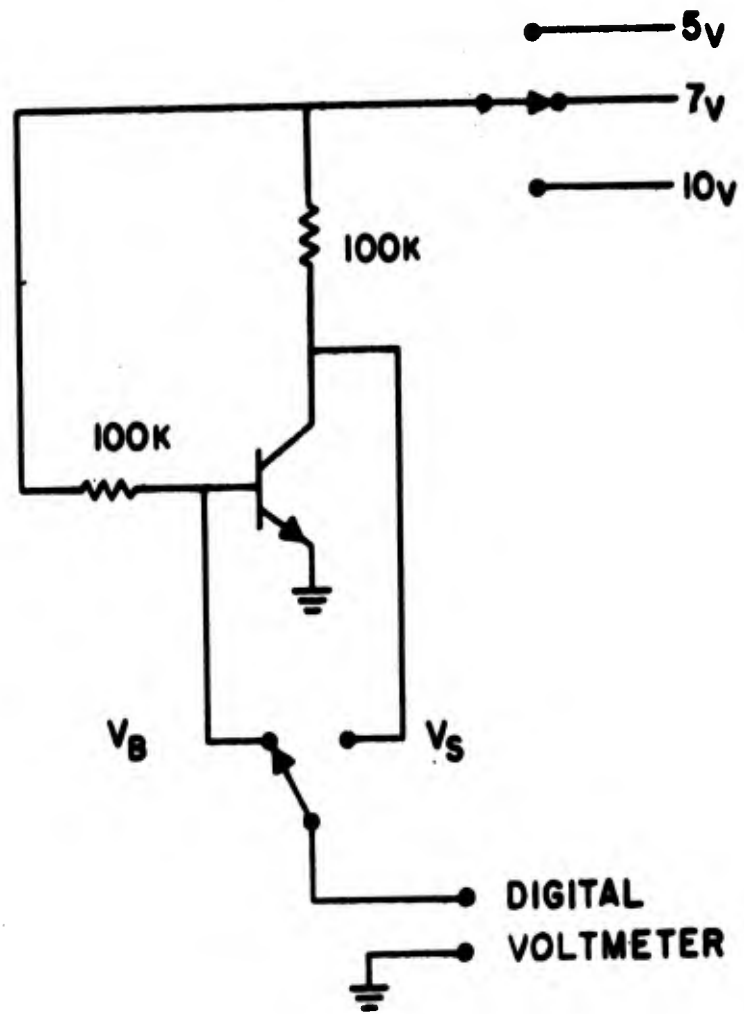


Figure 16. Test circuit to measure V_B and V_S .

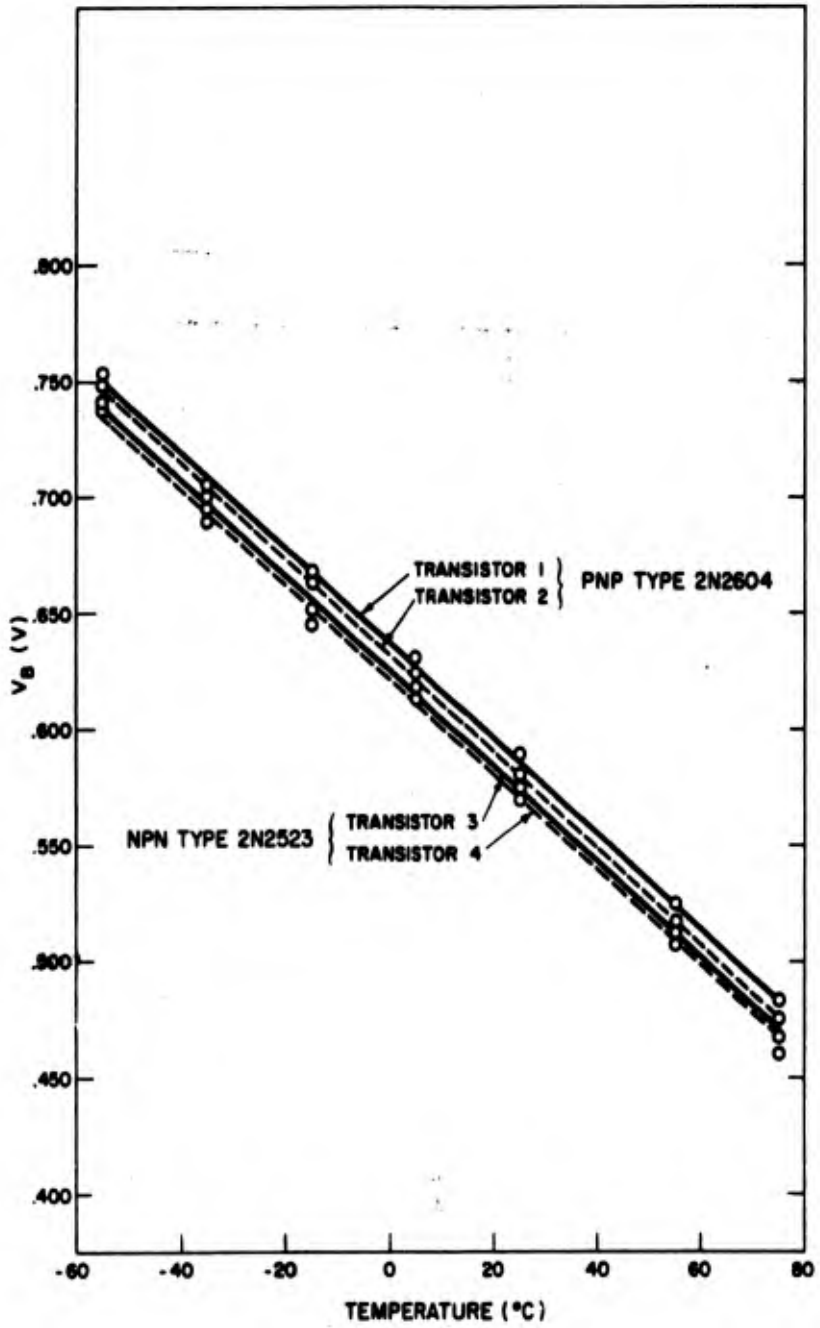


Figure 17. V_B versus temperature with 5-v supply.

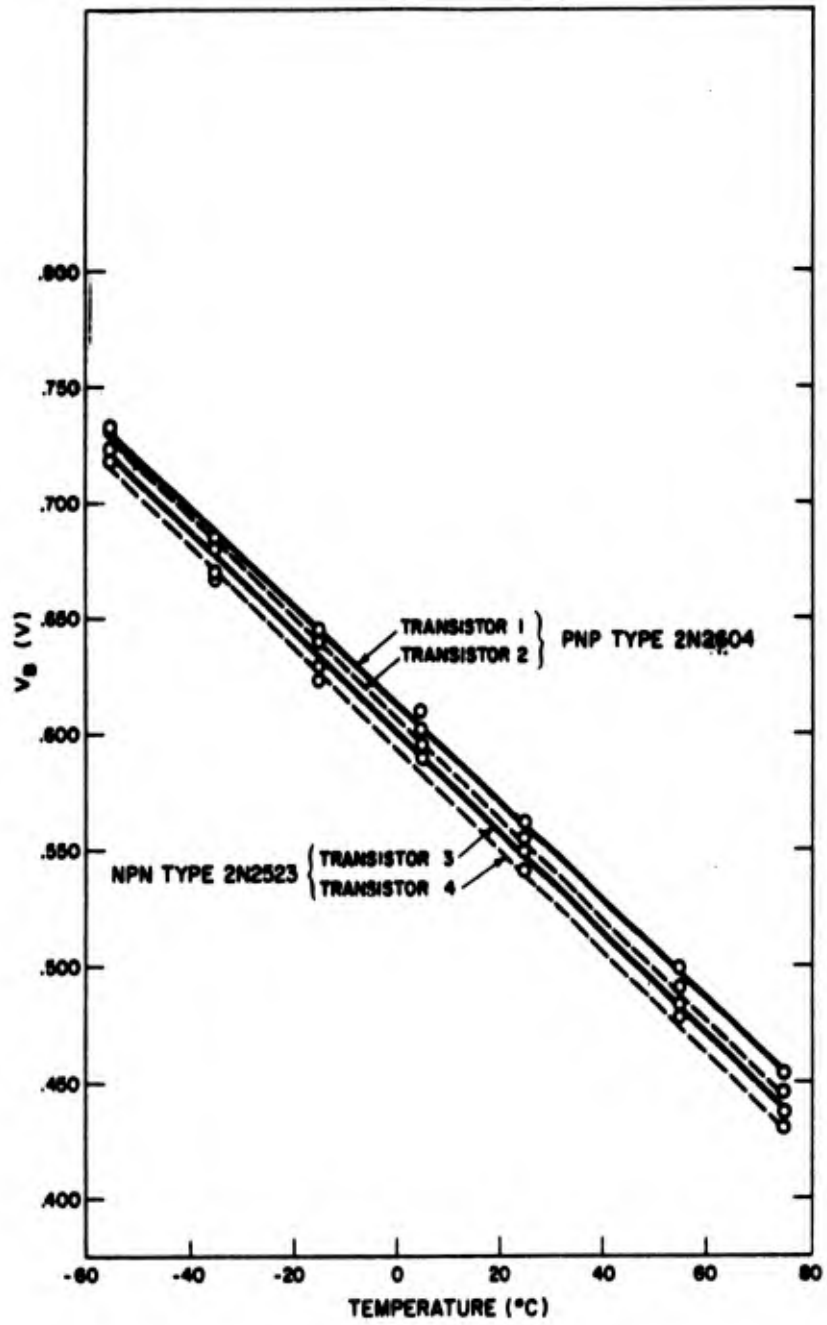


Figure 18. V_B versus temperature with 10-v supply.

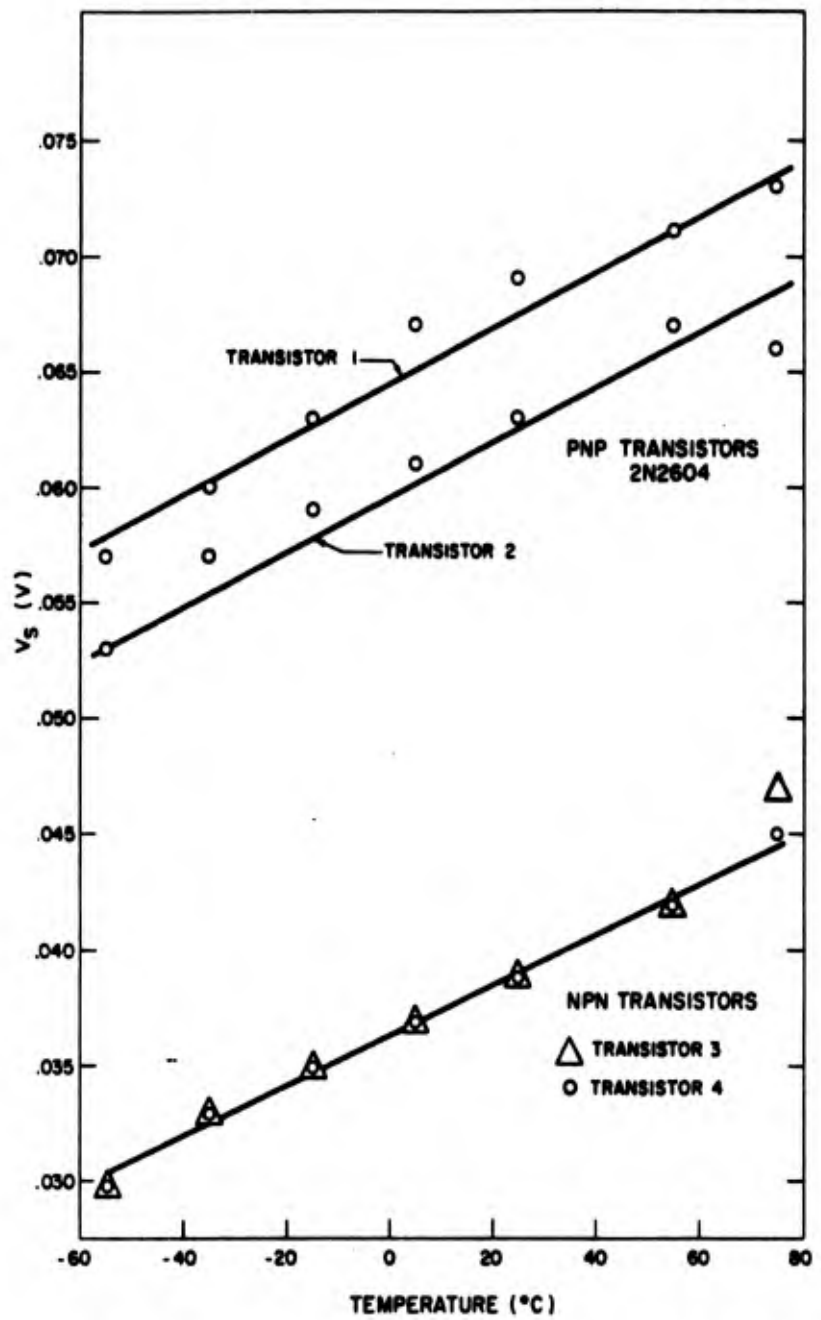


Figure 19. V_S versus temperature with 4.5-v supply.

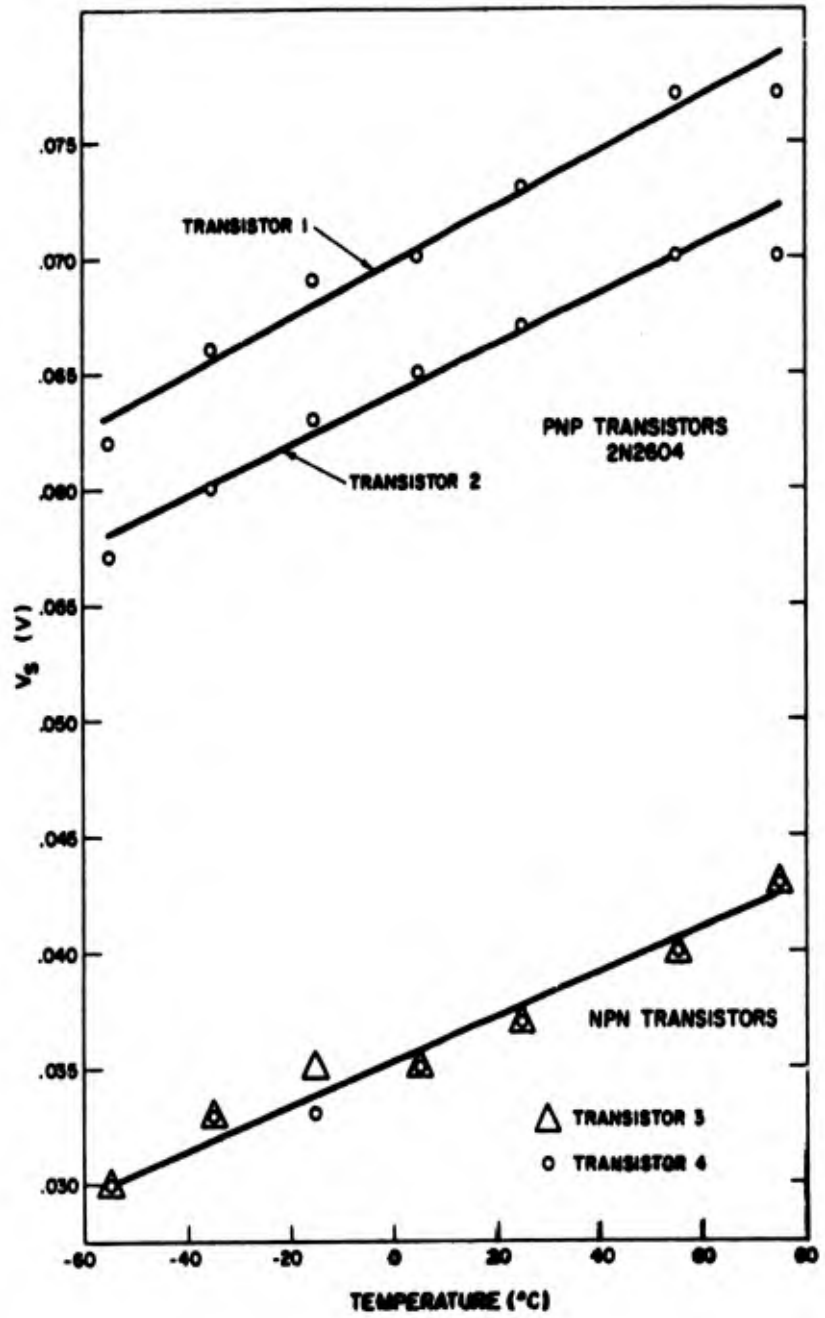


Figure 20. V_S versus temperature with 10-v supply.

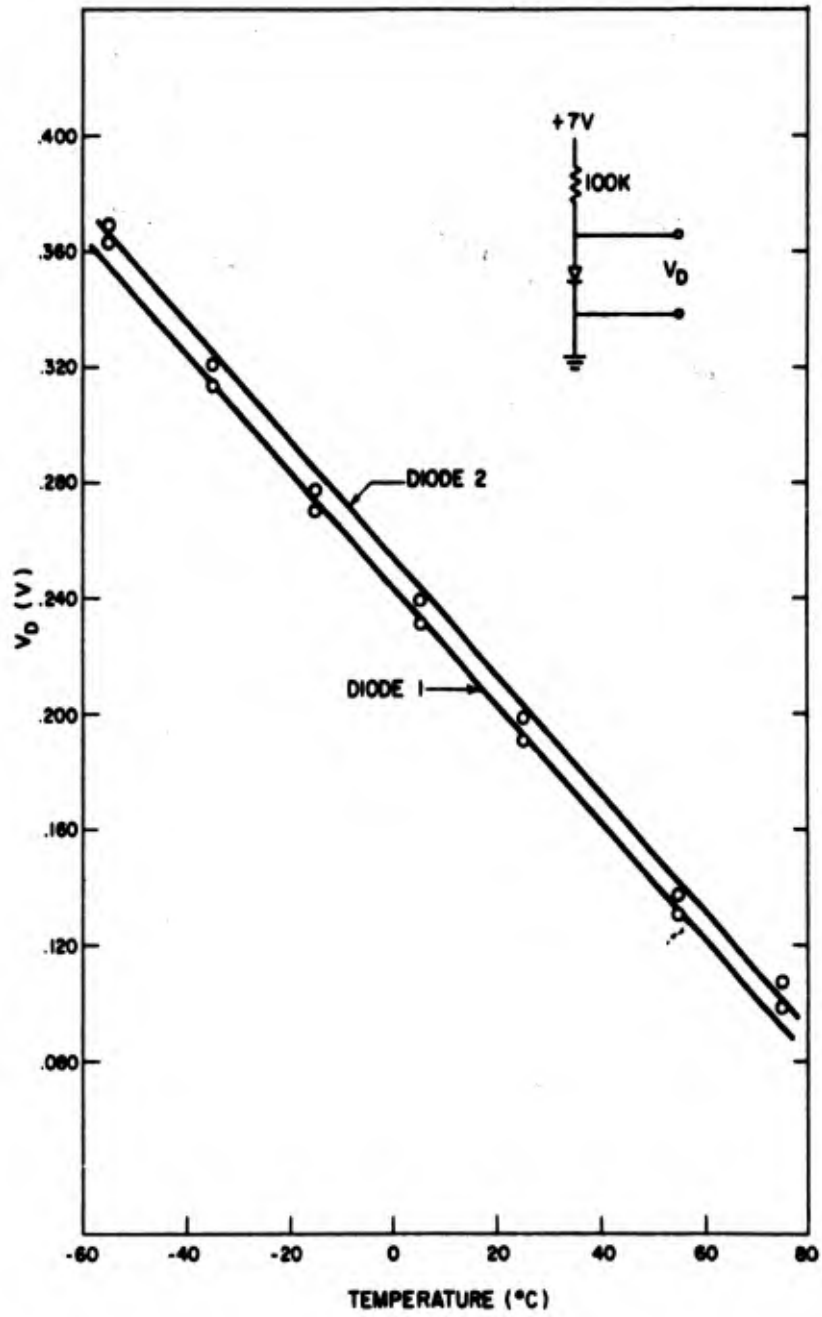


Figure 21. V_D versus temperature.

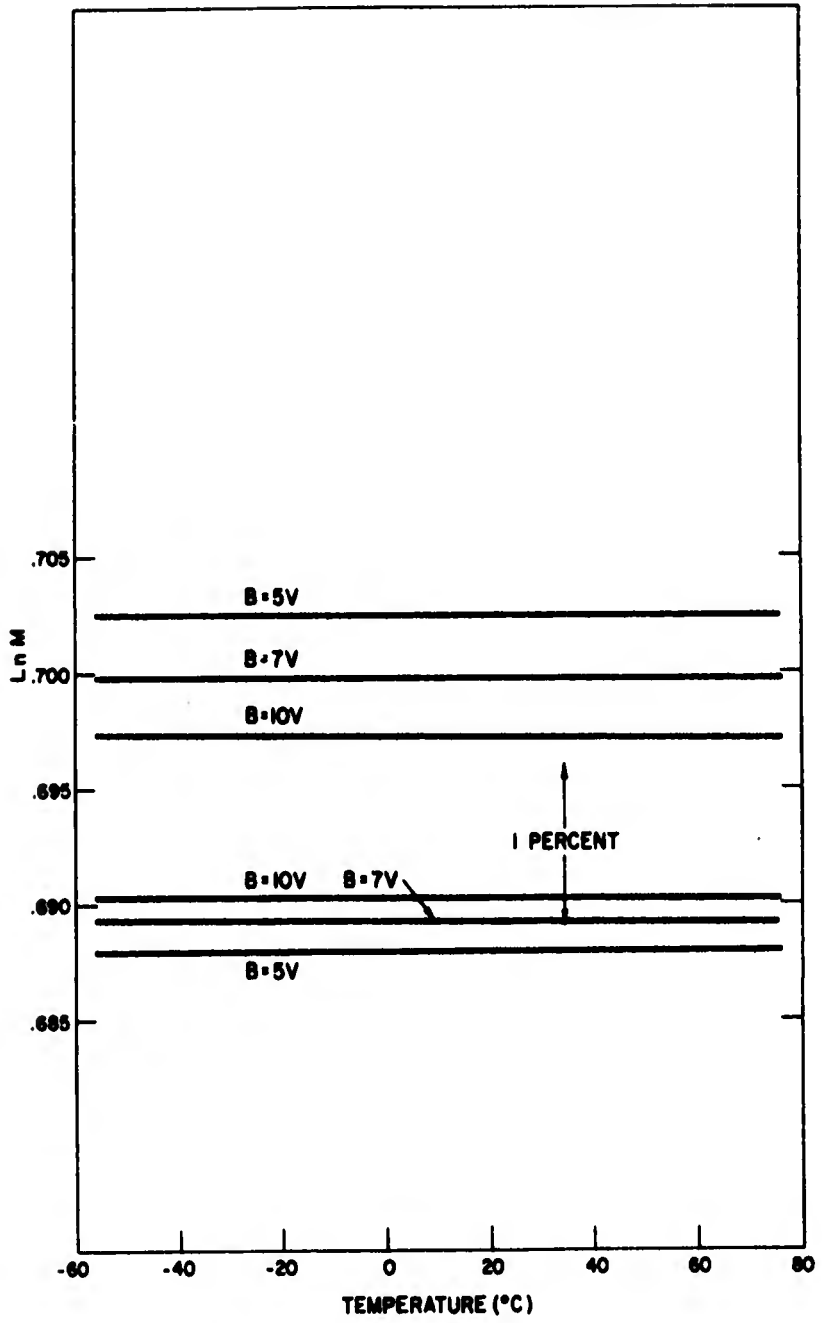


Figure 22. Ln M versus temperature.

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4. R-C oscillator
5. Astable multi-vibrators

A study was made to determine the limits to which the frequency of astable multivibrators could be stabilized against temperature and power-supply voltage variations so that they could be used as a time base in electric time fuses and programmers.

The temperature range was -55° to $+75^{\circ}\text{C}$, and the voltage variation was 20 percent. The frequency was about 100 cps. Four different circuits are developed. One circuit yielded ± 0.06 -percent frequency stability over the temperature and voltage range.

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