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FREQUENCY TEMPERATURE
COMPENSATION TECHNIQUES FOR
QUARTZ CRYSTAL
OSCILLATORS

first quarterly report

PIONEER-CENTRAL DIVISION
DAVENPORT, IOWA

THE *Bendix*
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Davenport, Iowa

Research Work for
Frequency Temperature Compensation
Techniques for Quartz Crystal Oscillators
in conjunction with Signal Corps
Technical Requirements SCL-6610B
dated 9 September 1963

First Quarterly Report for
Period 1 July 1963 to 30 September 1963

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1/ April 1964

Table of Contents

<u>Section Number</u>	<u>Title</u>	<u>Page Number</u>
1.1	Purpose	1
2.1	Abstract	2
3.1	Conferences	3
4.1	TCXO Design	4
4.2	Type III TCXO	12
5.1	Diode Switch	16
6.1	Frequency Adjustment	28
7.1	Crystal Characteristics	38
8.1	Voltage Regulation	43
9.1	Conclusions	50
10.1	Program for Next Quarter	51
11.1	Personnel Associated With the Project	52

Table of Figures

<u>Figure Number</u>	<u>Title</u>	<u>Page Number</u>
4.1	$\Delta f/f$ Versus V_o	5
4.2	Standard Oscillator Diagram	6
4.3	Modified Oscillator Diagram	6
4.4	$\Delta f/f$ Versus V_o	7
4.5	Oscillator Schematic	8
4.6	$\Delta f/f$ Versus V_o	9
4.7	Picture	10
4.8	Picture	11
4.9	Block Diagram	12
4.10	TCXO Schematic	13
5.1	Diagram of Diode Switch	16
5.2	Typical \varnothing Versus Temperature Curve	17
5.3	Thermistor Resistor Network	17
5.4	Schematic of Diode Switch	18
5.5	Diode Switch Circuit	20
5.6	Diode Switch Circuit	21
5.7	\varnothing Versus Temperature	22
5.8	V_o Versus Temperature	23
5.9	V_o Versus Temperature	24
5.10	V_o Versus Temperature	25
5.11	V_o Versus Temperature	26
5.12	Diode Switch Circuit	26
6.1	Capacitance, C_x , Versus PPM	29
6.2	C_x Versus Temperature	30
6.3	$d\varnothing/d C_x$ Versus Load Capacitance	31

6.4	Crystal and Load Capacitance	34
6.5	Oscillator Schematic	34
6.6	$\Delta f/f$ Versus V_o	37
7.1	TCXO $\Delta f/f$ Versus Temperature Curve	38
7.2	Compensation Curves	39
7.3	Compensation Curves	41
7.4	$\Delta f/f$ Versus Temperature	42
8.1	Voltage Regulator	44
8.2	Change in Voltage Output Versus Resistance	45
8.3	Output Voltage Versus Resistance	46
8.4	Power Consumption Versus Resistance	48
8.5	Power Consumption Versus Resistance	49

1.1 Purpose

The purpose of this project is to evolve a practical approach, both analytically and empirically, to the temperature compensation of quartz crystal oscillators. The study will be concentrated on developing units that are smaller, more reliable and having frequency temperature stabilities that have been previously achieved only at the cost of relatively high power consumption. The study will be concentrated on a nominal frequency of five megacycles, but will be generally applicable to AT cut quartz crystals of from 1 to 20 megacycles.

2.1 Abstract

This report discusses the results of investigation into the characteristics of temperature compensated crystal oscillators. A new compensation circuit using a diode switch is discussed and results are given on a number of experiments. Crystal and compensation networks are discussed to show the reasons for some types of non-linearities that occur in the $\Delta f/f$ versus temperature characteristics of TCXO's. Voltage regulation and voltage regulator requirements are shown and results of one voltage regulator circuit are given. The effect of adjusting frequency is shown and possible methods of obtaining negligible effect on the compensation characteristics are examined. The initial design of a miniature TCXO is presented.

3.1 Conferences

During this report period Signal Corps representatives visited at Pioneer-Central. The personnel involved were:

Signal Corps

Dr. Guttwein

Mr. Owen Layden

Mr. Stanley Schodowski

Pioneer-Central

Dr. Darrell E. Newell

Mr. Richard H. Bangert

The progress on Contract No. DA 36-039 AMC-02282(E) was reviewed. The requirements of the Type I, II and III oscillators were discussed. The general plan of the work to be done was outlined. Component tolerances and the requirements on TCXO components was discussed.

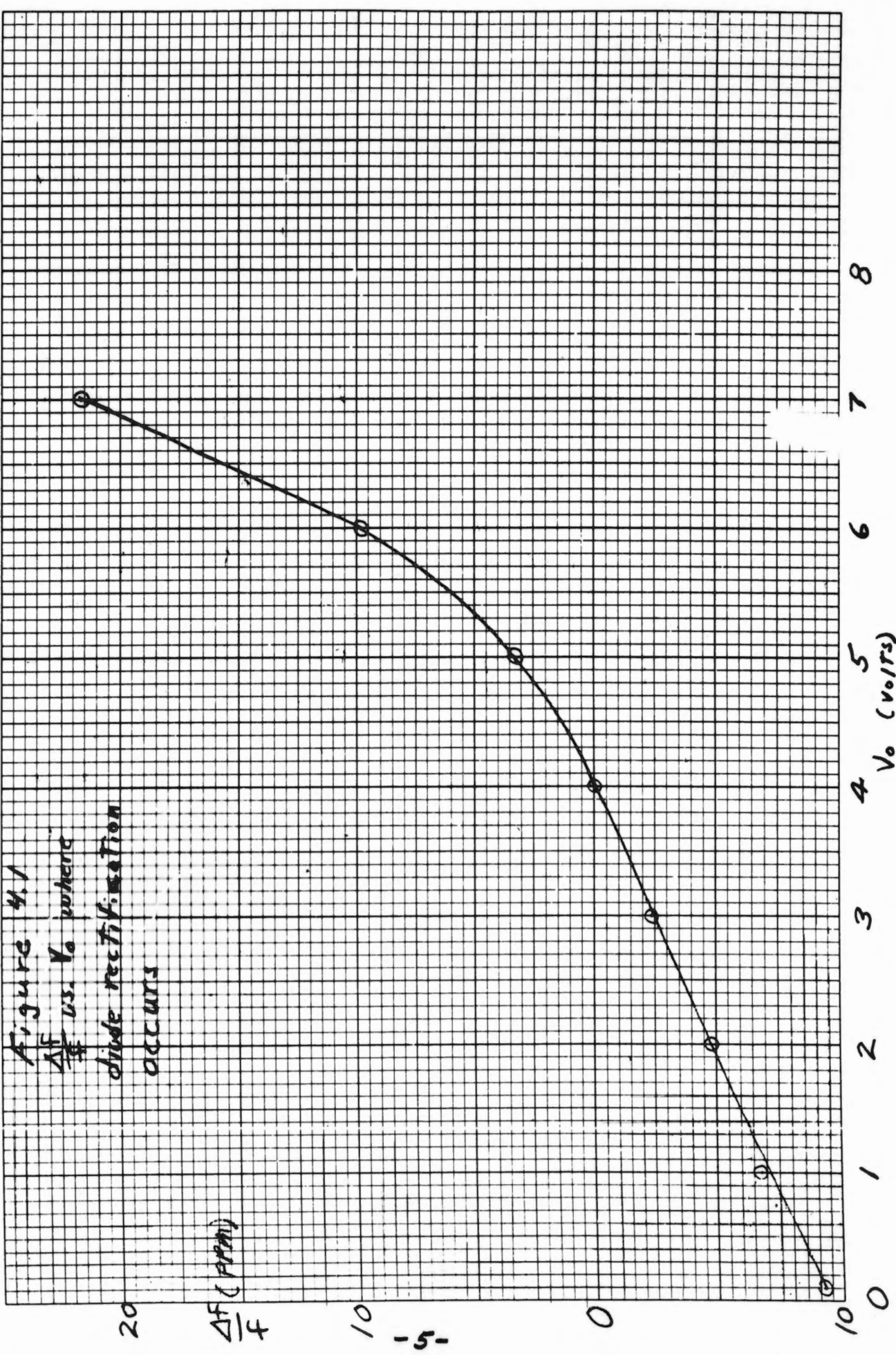
4.1 TCXO Design

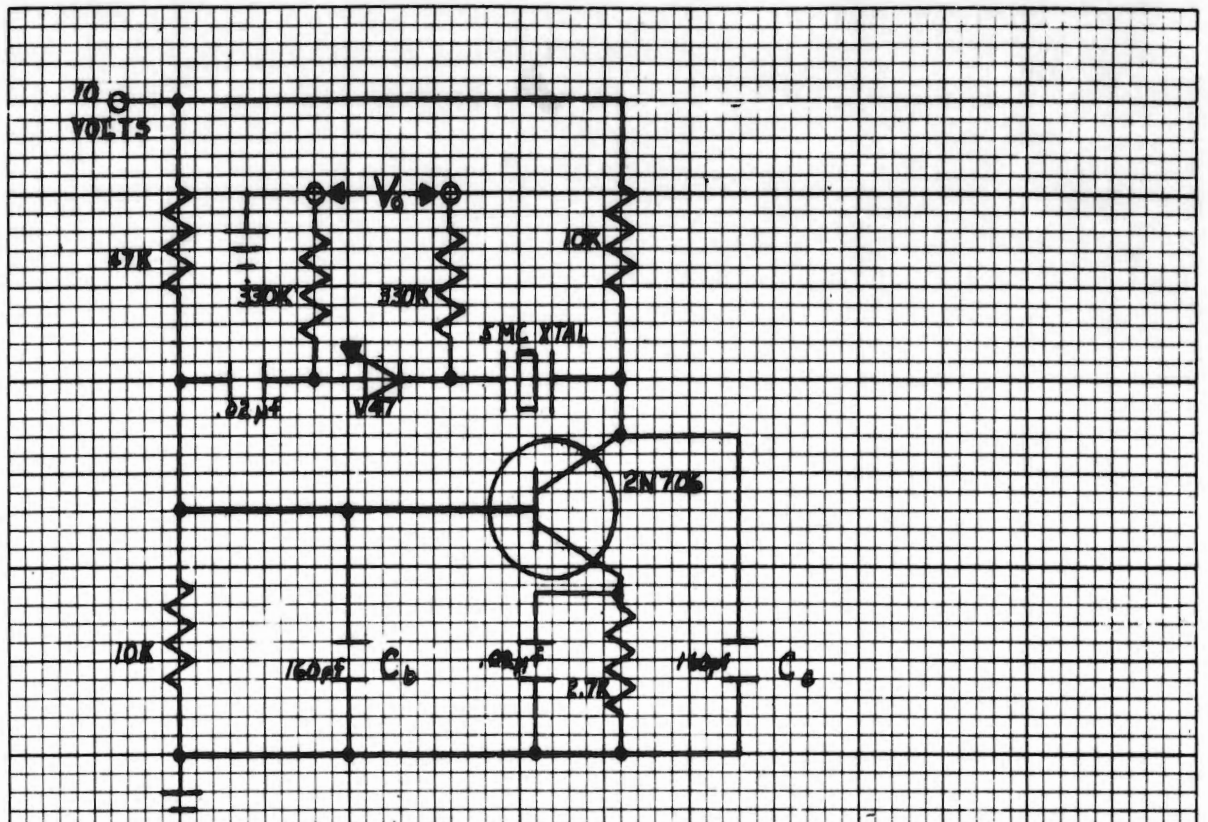
One of the most important factors in a TCXO is the drive level of the crystal and the A-C voltage across the varicap. As the drive level of a crystal changes the frequency will change. Sensitivity to slight changes in drive level cannot be tolerated in a TCXO, therefore the drive level should be kept as low as possible. When the A-C signal across a varicap exceeds the DC reverse bias voltage, self rectification will occur. This limits the lowest voltage at which the varicap can be biased. Figure 4.1 shows a $\Delta f/f$ versus V curve where self rectification occurs. This particular curve is rather drastic, but illustrates the effect of self rectification. Also, as the β of the transistor changes with temperature, the A-C voltage across the varicap will change causing the voltage at which self rectification occurs to vary with temperature.

Figure 4.2 shows the standard oscillator configuration that is used. To keep the drive level and A-C swing on the varicap low while still maintaining a reasonable output voltage requires that the biasing on each transistor be adjusted for some optimum operation. Doing this may result in a distorted sine wave output. Figure 4.3 is the first modification in the basic circuit that was used to lower the drive level in the oscillator. The un-bypassed emitter resistance provides negative feedback which decreases the amplitude of oscillation and helps stabilize the output voltage. This results in a decreased signal at the collector as R_e is increased. The output waveform distortion will also decrease as R_e is increased. Figure 4.4 shows the effect of changing the amount of un-bypassed emitter resistance.

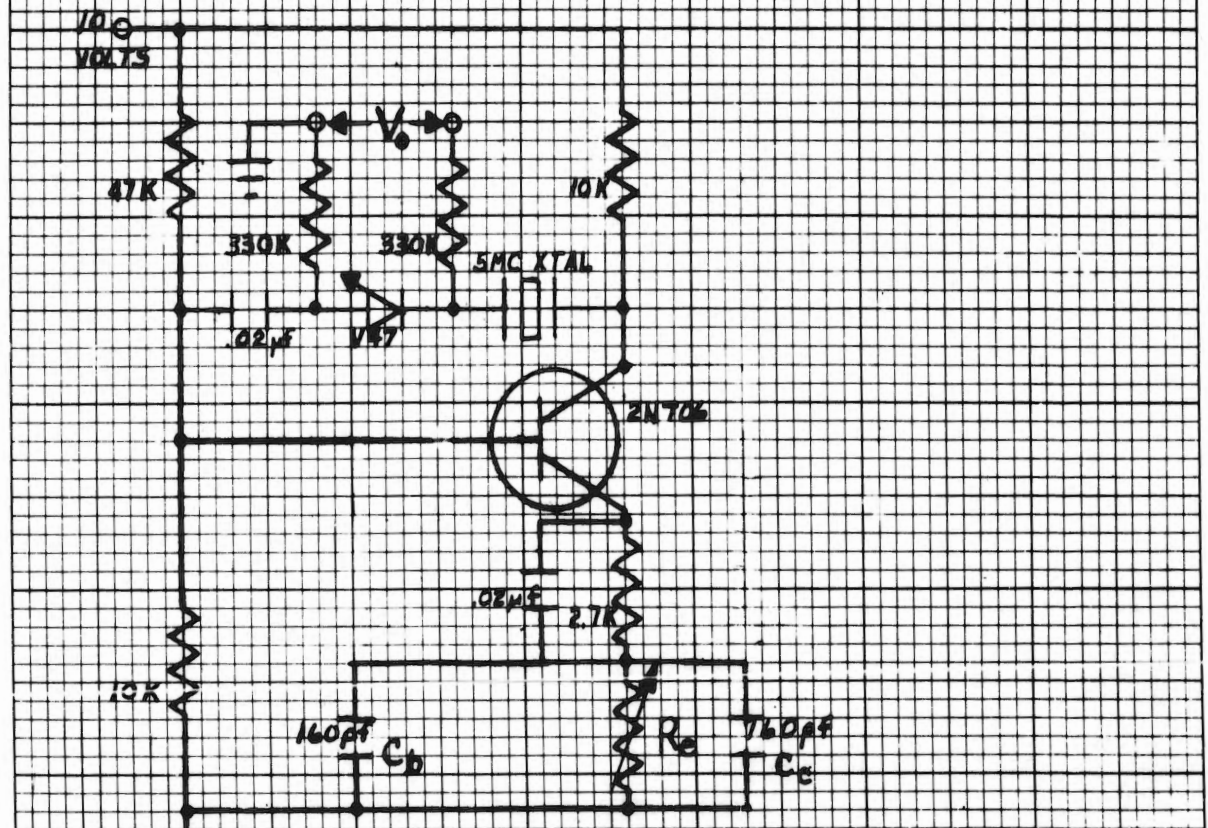
Figure 4.5 shows the other circuit that was partially investigated. This configuration effectively decouples the resonant circuit from the active network. Two things are accomplished by doing this. One is that the circulating current in the resonant tank circuit is decreased and the other is that changes in the

Figure 4.1
 $\frac{\Delta F}{F}$ vs. V_0 where
diode rectification
occurs

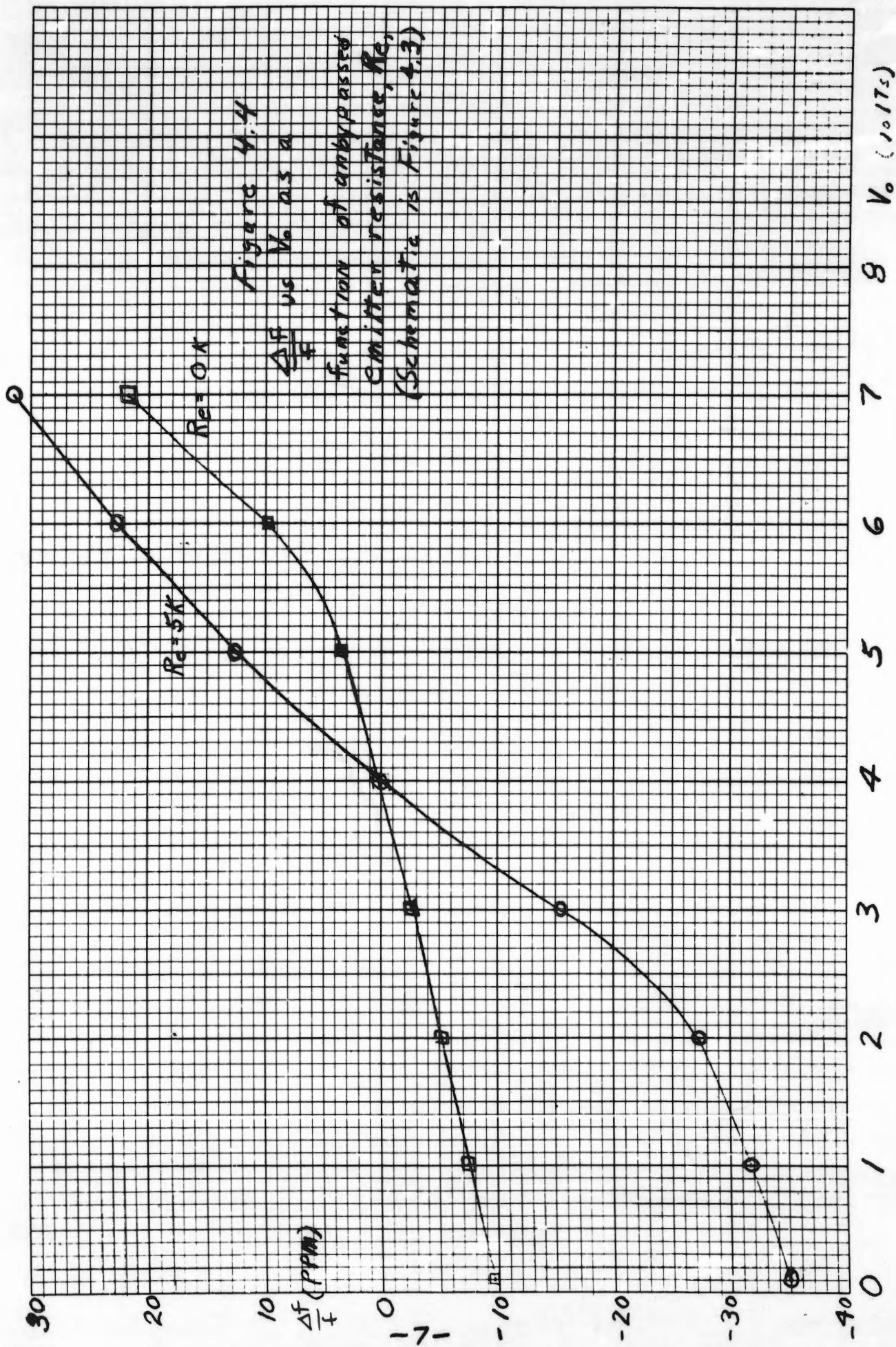




STANDARD OSCILLATOR DIAGRAM
FIGURE 4.2



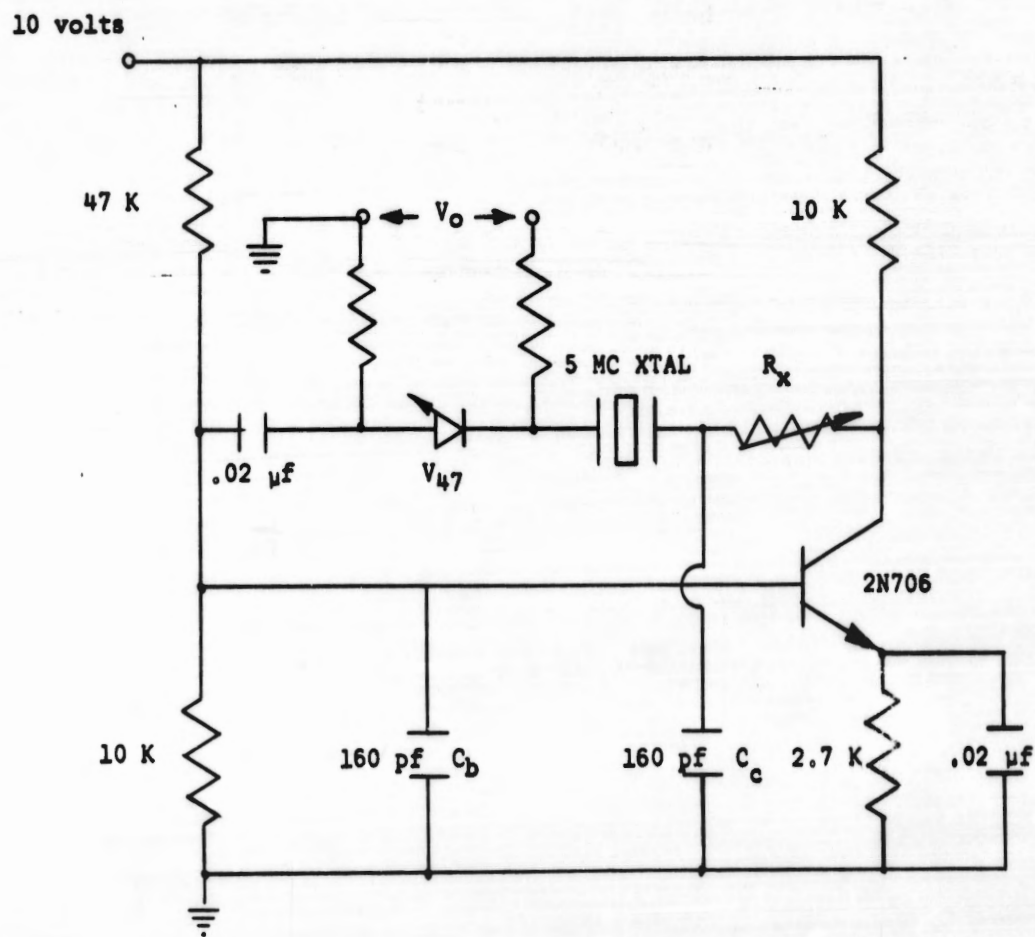
MODIFIED OSCILLATOR DIAGRAM
FIGURE 4.3



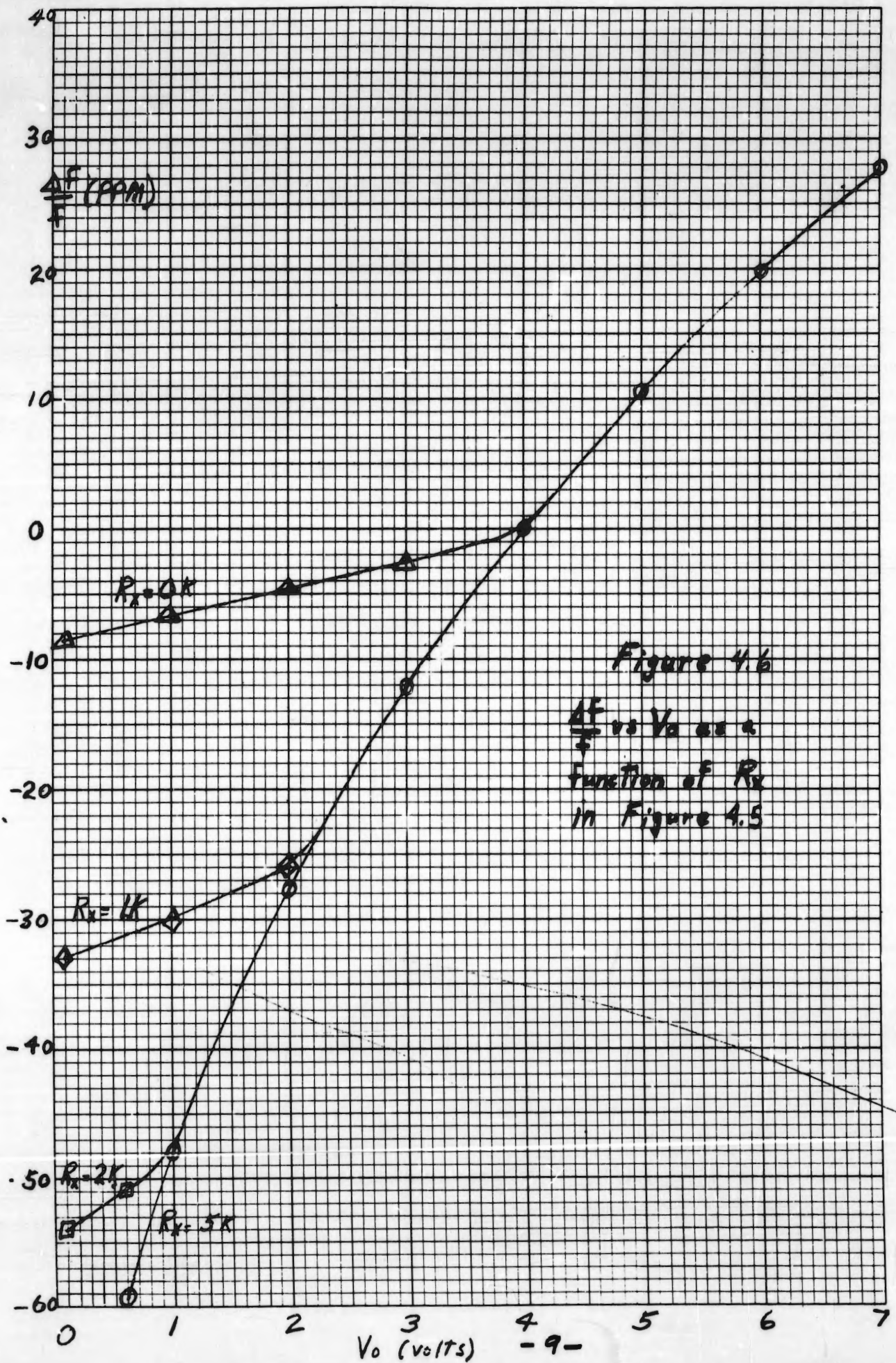
active circuit parameters have less effect on the resonant circuit. Some of the results of the initial investigation are given in the following Figure 4.6.

Figure 4.6 shows the effect of increasing R_x on the $\Delta f/f$ versus voltage curve.

Further investigation is being carried on to determine the other advantages and disadvantages resulting from this circuit configuration.



Oscillator Schematic
Figure 4.5



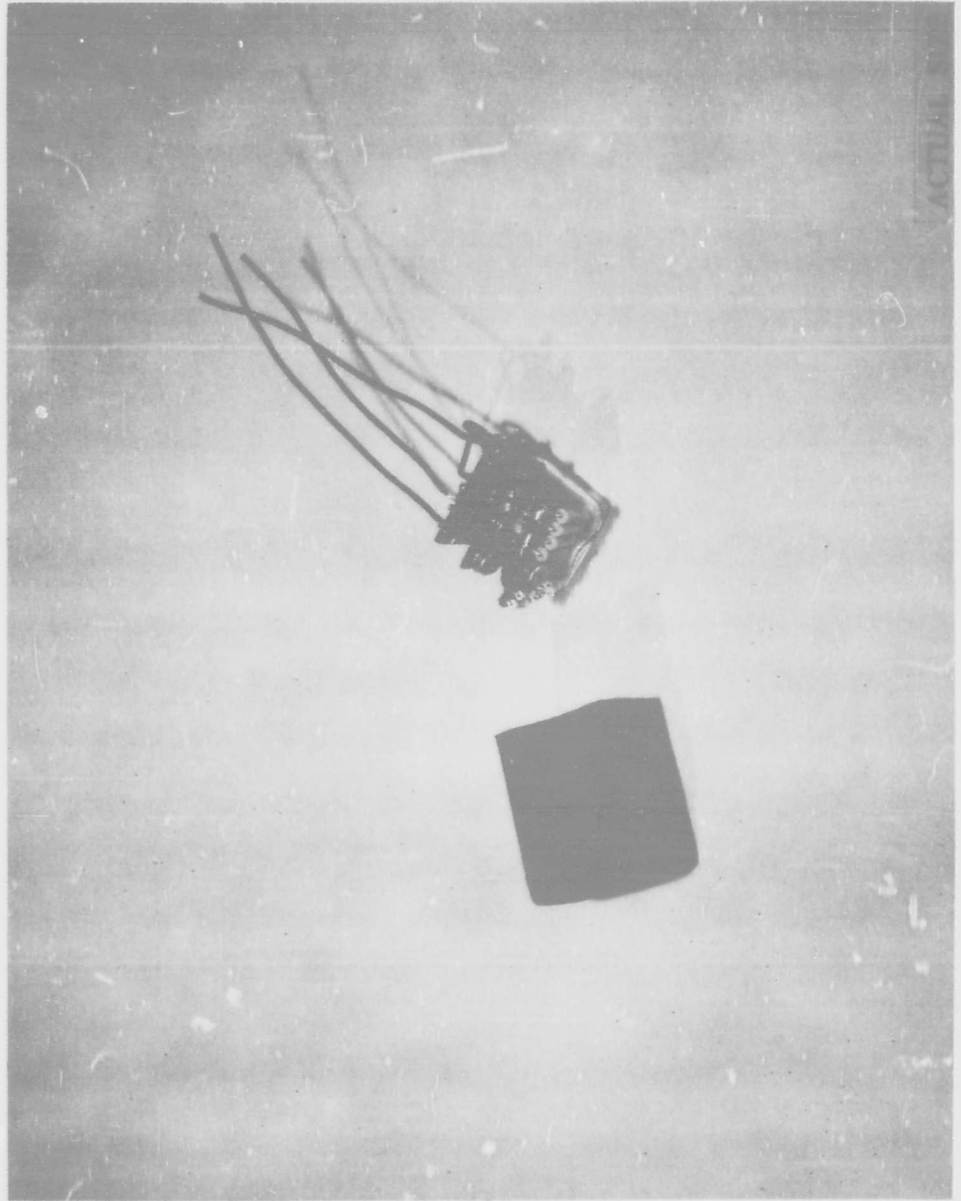


Figure 4.7

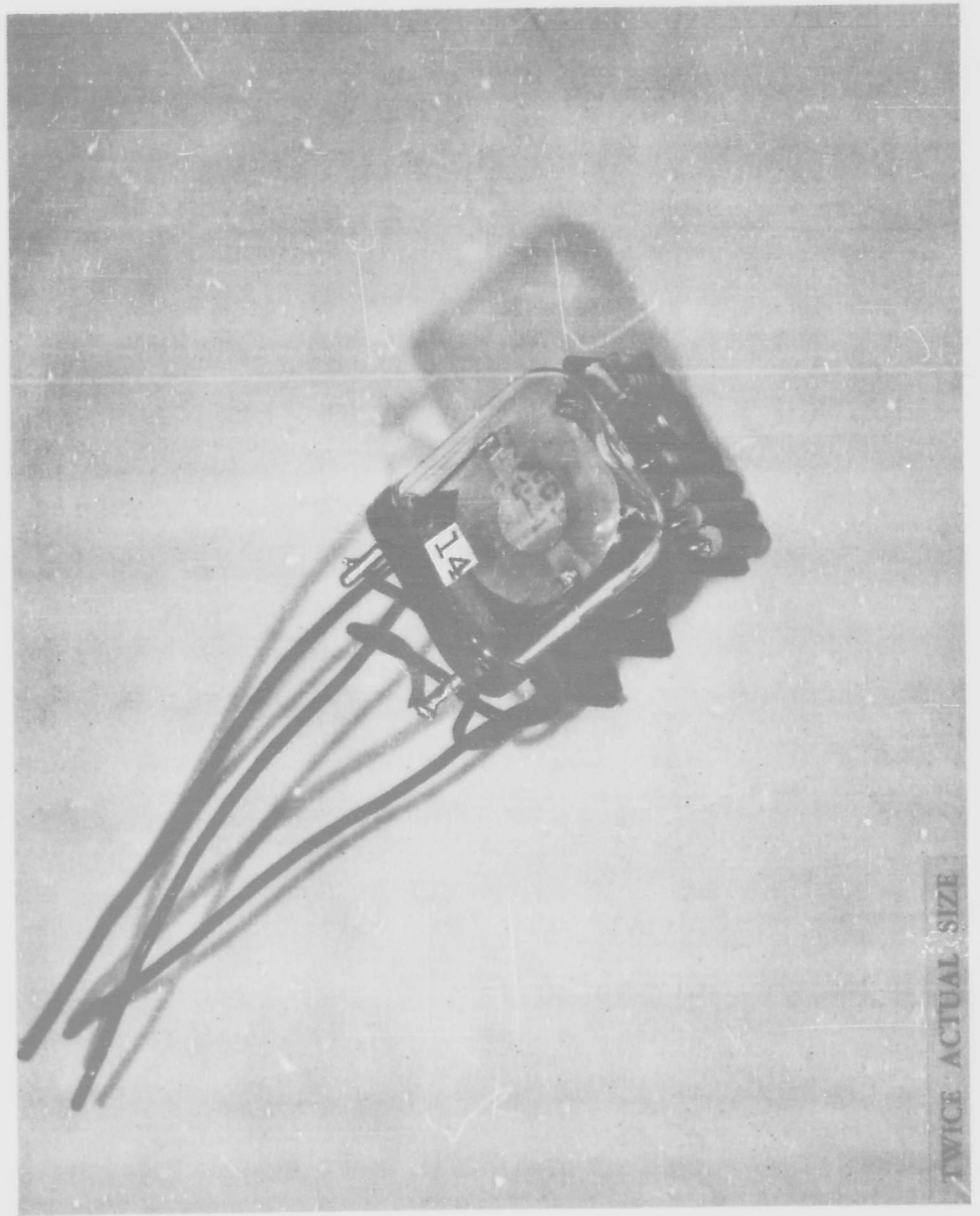
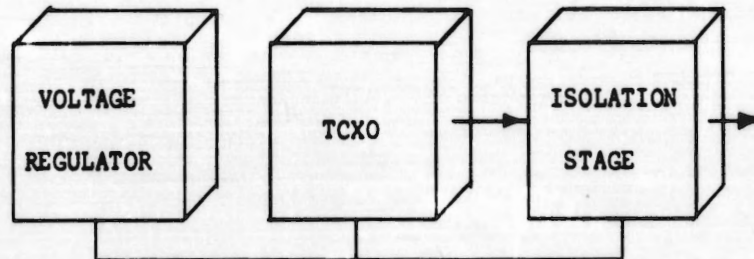


Figure 4.6

4.2 Type III TCXO

One of the phases of the work this quarter was to investigate the required circuit design and physical construction of a TCXO to be within the dimension of 0.6" x 0.7" x 1.5". The breadboard oscillator that was constructed is shown in Figure 4.7 and 4.8 and has the smallest volume of any built to date. The largest problem in designing a TCXO to conform to very small dimensional requirements is the fact that the performance of many components is degraded as the size is reduced. The block diagram in Figure 4.9 and schematic in Figure 4.10 illustrates the minimum number of stages that can be tolerated for a general design oscillator where the load is not specified to a very close tolerance.



Block Diagram
Figure 4.9

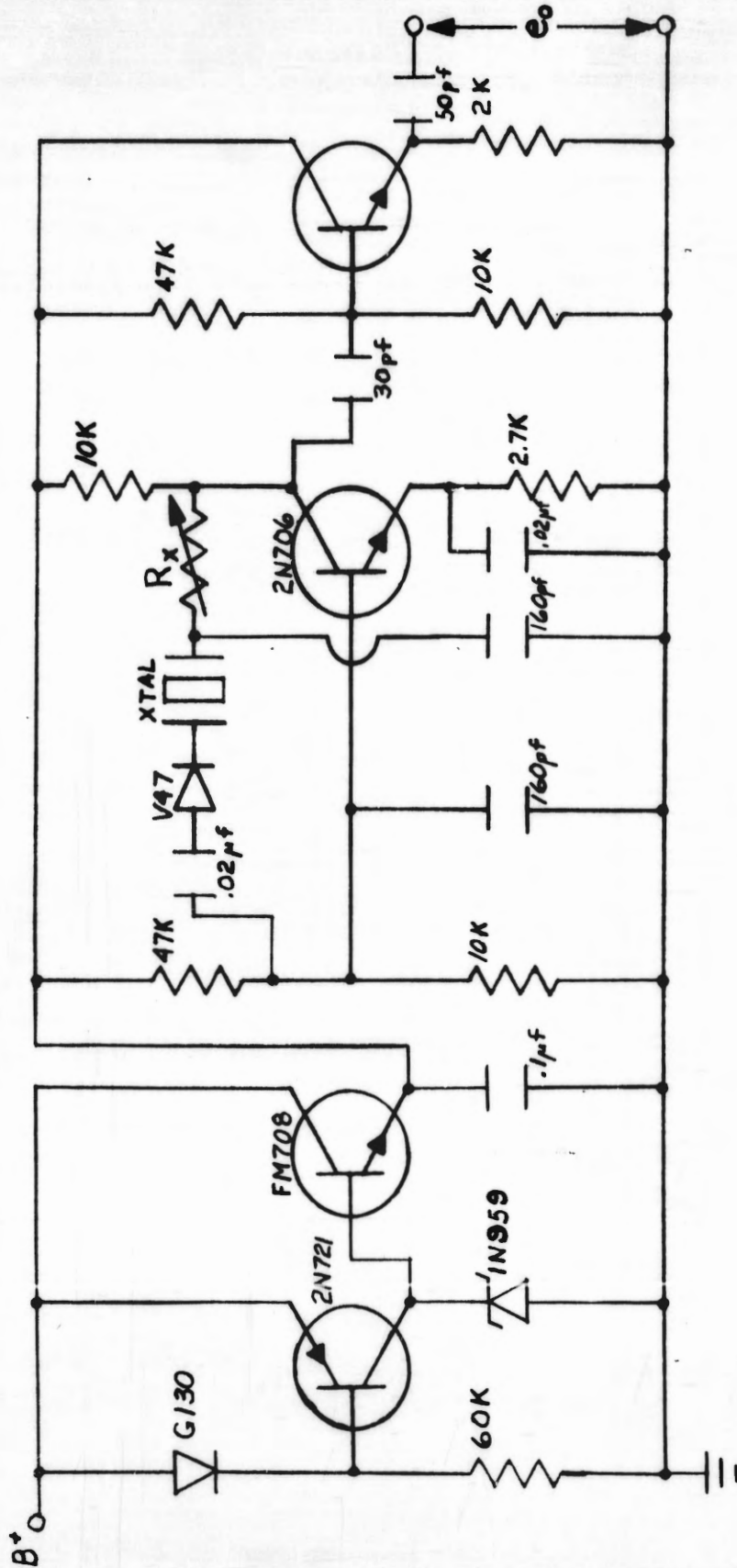


FIGURE 4.10

Table I lists the specification of the TCXO.

- 1) Frequency Temperature Stability: $\pm 5 \times 10^{-8}$ over the ambient temperature range of -5°C to $(65^{\circ}\text{C} + \frac{P_T}{3})$ where P_T is total oscillator power dissipation
- 2) Frequency Tolerance: $\pm 1 \times 10^{-7}$
- 3) Frequency Adjustment Range: $\pm 1 \times 10^{-6}$
- 4) Temperature Transient: A positive or negative thermal step function within ambient temperature limits.
- 5) Humidity: Maximum relative humidity of 100%
- 6) Power Input: 50 milliwatts
- 7) Maximum Available Supply Voltage Regulation: 10%

The voltage regulator is required because of the dependence of the TCXO characteristics upon the stability of the B+ voltage. The requirements of the regulator are that regulation of better than 0.01% is desired. The volume and power requirements are such that a complex voltage regulation circuit cannot be used to obtain this stability.

The TCXO section is basically as shown in previous reports. A discussion of the TCXO circuit was given previously.

The isolation stage is as shown in Figure 4.10. It is simply a grounded collector stage to prevent impedance changes in the load from affecting the frequency and compensation of the TCXO.

The greatest difficulty encountered in the initial design of this oscillator was not in the circuitry but in the physical layout and construction of the oscillator. The capacitors present the greatest problem. The stability and

temperature compensation requirements that the TCXO places on the rf capacitors virtually eliminates ceramic capacitors which are available in extremely small sizes. The best capacitors for the size are silver mica capacitors such as the Arco DM-10 series. Ceramic capacitors in the 0.01 μ f to 0.03 μ f range are suitable for bypass capacitors and are available with dimensions of approximately a 1/10 watt carbon resistor. One-eighth watt metal film resistors are used in the TCXO with 1/10 watt carbon composition resistors used in the isolation stage. The transistors used are in a TO-46 package.

The present unit that is being designed is to be "potted." This will enable "single-dipped" capacitors, the single chip transistors, and coated instead of molded bypass capacitors to be used which will allow the size to be reduced further. The present unit did not use printed circuit boards, but the one being designed now will be built on printed circuit boards which will make assembly much easier. The compensation network will be mounted to pins located on the top board of the circuit and will be with the rest of the circuit. The crystal pins will be at the same end of the package as the thermistor network and they will be thermally tied to the compensation network to reduce the effect of temperature transients.

Other types of construction have been considered, and may be tried in an effort to further reduce the size to add a stage of amplification. The size somewhat restricts the type of construction that can be used.

5.1 Diode Switch

An improvement in the versatility of the voltage divider control networks has been devised and investigated during this quarter. Figure 5.1 is a schematic of the circuit referred to as a "diode" switch.

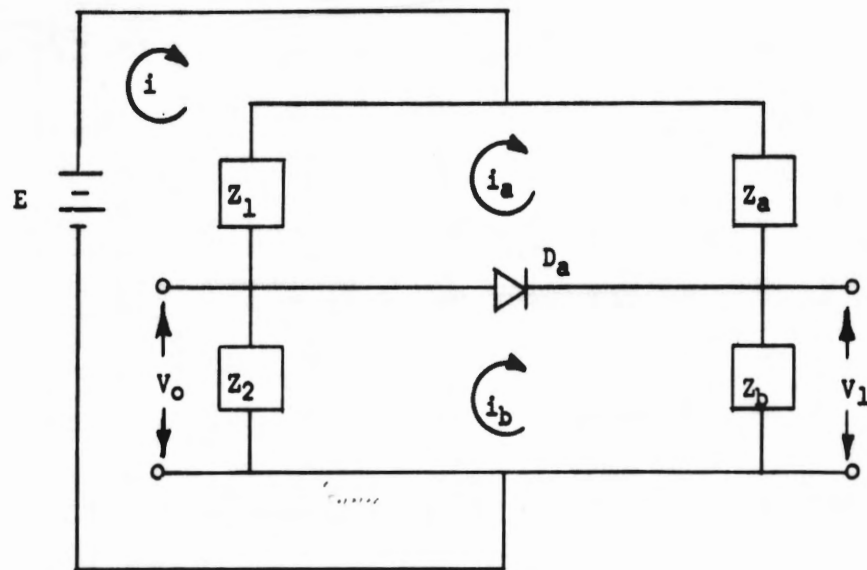


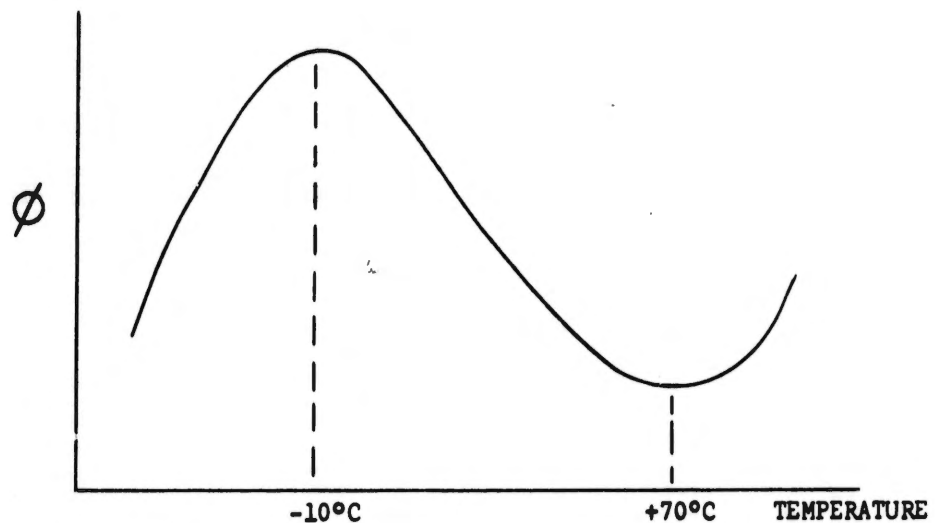
Diagram of Diode Switch

Figure 5.1

Z_1 , Z_2 and E are the basic components of the voltage divider network discussed in previous reports. Z_a and Z_b and the diode, D_a , are the basic parts of the diode switch. The problem that resulted in this circuit being devised is that of providing the required compensation voltage characteristics around the upper turning point temperature of the crystal. For low angle crystals, it was found from previous work that it was very difficult to generate the required change in slope of the $\Delta f/f$ versus V curve at the upper turning point. This was due mostly to the fact that thermistors at the higher temperatures are changing less and the resistance of the entire circuit is becoming small. When the

thermistor resistance gets less as temperature increases, changing the total resistance becomes correspondingly more difficult to change in a specific manner.

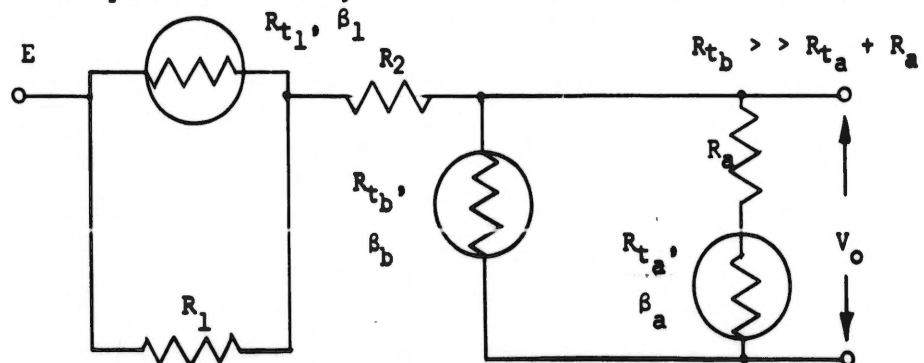
To overcome this problem, a method was needed where the Z_1/Z_2 ratio (ϕ) could be forced to change as required at the high temperature end. As can be seen from Figure 5.2, ϕ changes slope at the upper turning point. To change the slope of ϕ in this manner, Z_1 has to very abruptly approach a zero



Typical ϕ Versus Temperature Curve

Figure 5.2

slope and at the same time Z_2 has to start decreasing very rapidly. This requirement is impossible to meet, because the thermistor's characteristics do not

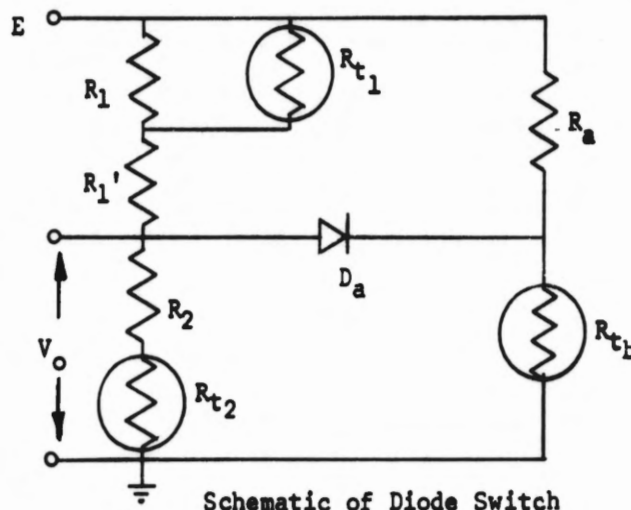


Thermistor Resistor Network

Figure 5.3

change at the rate required. A curve similar to the one shown in Figure 5.2 can be generated by using a circuit like that shown in Figure 5.3, but the change in slope occurs over a wider temperature range than is required. Consequently, a new scheme for generating the required θ was necessary.

The best results were obtained using the diode switch. Figure 5.4 shows the basic circuit for controlling the rate of change of θ at the upper turning point.



Schematic of Diode Switch
Figure 5.4

The following equations derive the expression that governs the effect of the diode switch. Figure 5.1 is used for the symbols in the equations. Z_T is the resistance of the diode.

Equation 1
$$V_o = E Z_2 \left[\frac{Z_1 Z_b + Z_a Z_b + Z_a Z_T + Z_b Z_T}{Z_1 Z_b (Z_2 + Z_T + Z_a) + Z_a Z_2 (Z_b + Z_T + Z_1) + Z_T (Z_1 Z_a + Z_b Z_2)} \right]$$

where
$$\frac{Z_1}{Z_2} > \frac{Z_a}{Z_b}, \quad V_o = E \frac{Z_2}{Z_1 + Z_2}$$

To put Equation 1 in a different form assume the following,

Equation 2
$$\theta_1 = Z_1/Z_2$$

Equation 3
$$\theta_a = Z_a/Z_b$$

Equation 4

$$V_0 = E \left[\frac{Z_1 + Z_a + Z_T (1 + \theta_a)}{Z_1 (1 + \theta_a) + Z_a (1 + \theta_1) + Z_T (1 + \theta_a) (1 + \theta_1)} \right]$$

Let $\frac{E}{V_0} - 1 = \theta_c$

Equation 5

$$\theta_c = \frac{Z_1 \theta_a + \theta_1 [Z_a + Z_T (1 + \theta_a)]}{Z_1 + Z_a + Z_T (1 + \theta_a)}$$

The equations governing the diode switch are complex and are further complicated by the fact that the diode resistance is a non-linear function of bias voltage and current. Usually an empirical approach to the determination of the required network for Z_a and Z_b is faster and simpler. The following procedure outlines the manner in which the required network values can be determined empirically. This procedure is for compensation at or above the upper turning point temperatures, but it can be applied at the low temperature end if the change in voltage slope, etc. are taken into account.

1. It is assumed that the components Z_1 and Z_2 have been obtained previously and compensation is achieved up to the upper turning point. The upper turning point will be assumed to be at 60°C.

2. Let Z_a and Z_b be decade boxes. Let Z_a equal to a fixed value and plot $\Delta f/f$ versus Z_b for a range of resistance around the point where the diode conducts. Do this for a number of values of Z_a at 60°C, 70°C, etc. As the value of Z_a becomes smaller, the larger the effect will be on the frequency. Values of Z_a from $Z_a = Z_1$ to $Z_a = 10 Z_1$ at 60°C are typical.

3. After the $\Delta f/f$ versus Z_b as a function of Z_a have been obtained at each temperature, plot them on a graph of $\Delta f/f$ versus Z_b . From this graph make a table where Z_b is the resistance versus temperature characteristics that make $\Delta f/f = 0$ at each temperature for each value of Z_a .

4. The Z_b temperature as a function of Z_a characteristics that are obtained in Step 3 are some of the possible R versus temperature characteristics that will result in a zero change in frequency versus temperature for the high temperatures. The only step remaining is to determine an appropriate thermistor resistor network for Z_b .

The circuit in Figure 5.4 can be altered slightly to obtain more versatility and to reduce the diode forward resistance characteristics on the Z_b versus temperature requirements. This is shown in Figure 5.5.

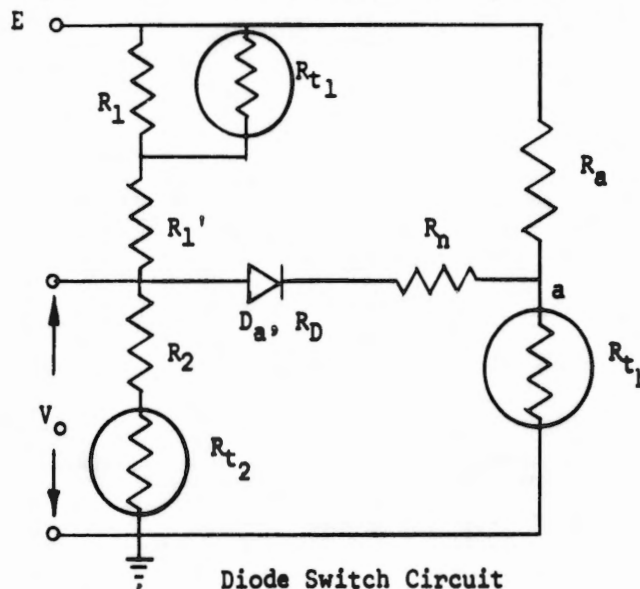


Figure 5.5

In the preceding mathematical analysis, R_n is included in Z_T , where Z_T is composed of $(R_D + R_n)$. R_n does not alter the empirical determination of the required R_b versus temperature characteristics. R_n only serves to adjust the effect of the diode switch on the voltage V_o . The larger R_n is, the less the change in V_o versus resistance R_{T_b} will be.

This technique used to compensate for the temperatures around the upper turning point has been used very successfully. The stability achieved using this method for low angle crystals is better than that achieved using only the voltage divider, Z_1 and Z_2 networks.

The circuit shown in Figure 5.6 was used to obtain data on the particular network shown. Figure 5.7 is a plot of the ratios $Z_1/Z_2 = \theta_1$ and $Z_a/Z_b = \theta_a$ versus temperature. θ_x is also plotted where θ_x is the ratio of

$$\frac{Z_1 \parallel Z_a}{Z_2 \parallel Z_b} \quad \parallel = \text{parallel}$$

indicating what would result if the diode were shorted. Figure 5.8 is a plot of the voltages versus temperature obtained. V_{o_1} is the voltage, V_o , that would result if the diode was open circuited. V_{o_a} is the voltage generated at point a if the diode was open circuited. V_{o_t} is the voltage generated with the diode in the circuit. Figure 5.9 shows the resulting effect of changing R_a on the V_o versus temperature curves and Figure 5.10 shows the effect of changing R_b .

The diode switch can also be used for compensation at the low temperature end. The low angle crystal does not only present problems at the upper turning point, but also is difficult to compensate at temperatures below the lower turning point temperatures. The diode switch is not quite as effective at the lower turning point as it is at the upper turning point. The reason for this is indicated in Figure 5.11. Curve 1 is the required V_o versus temperature curve.

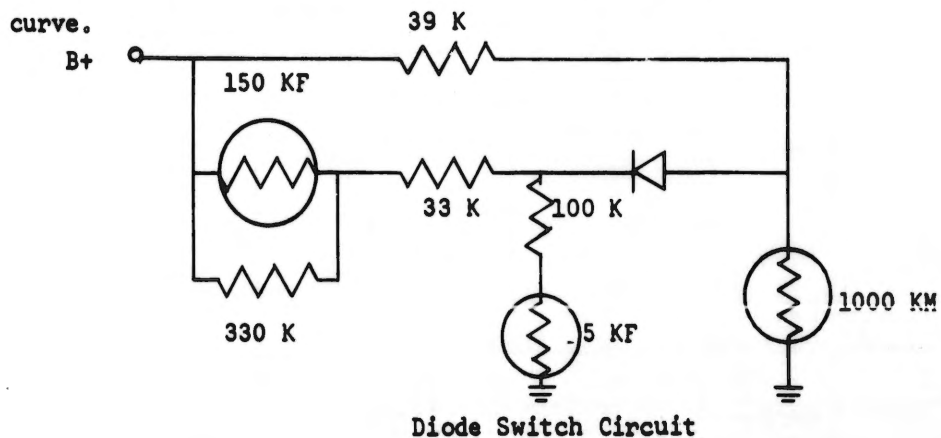


Figure 5.6

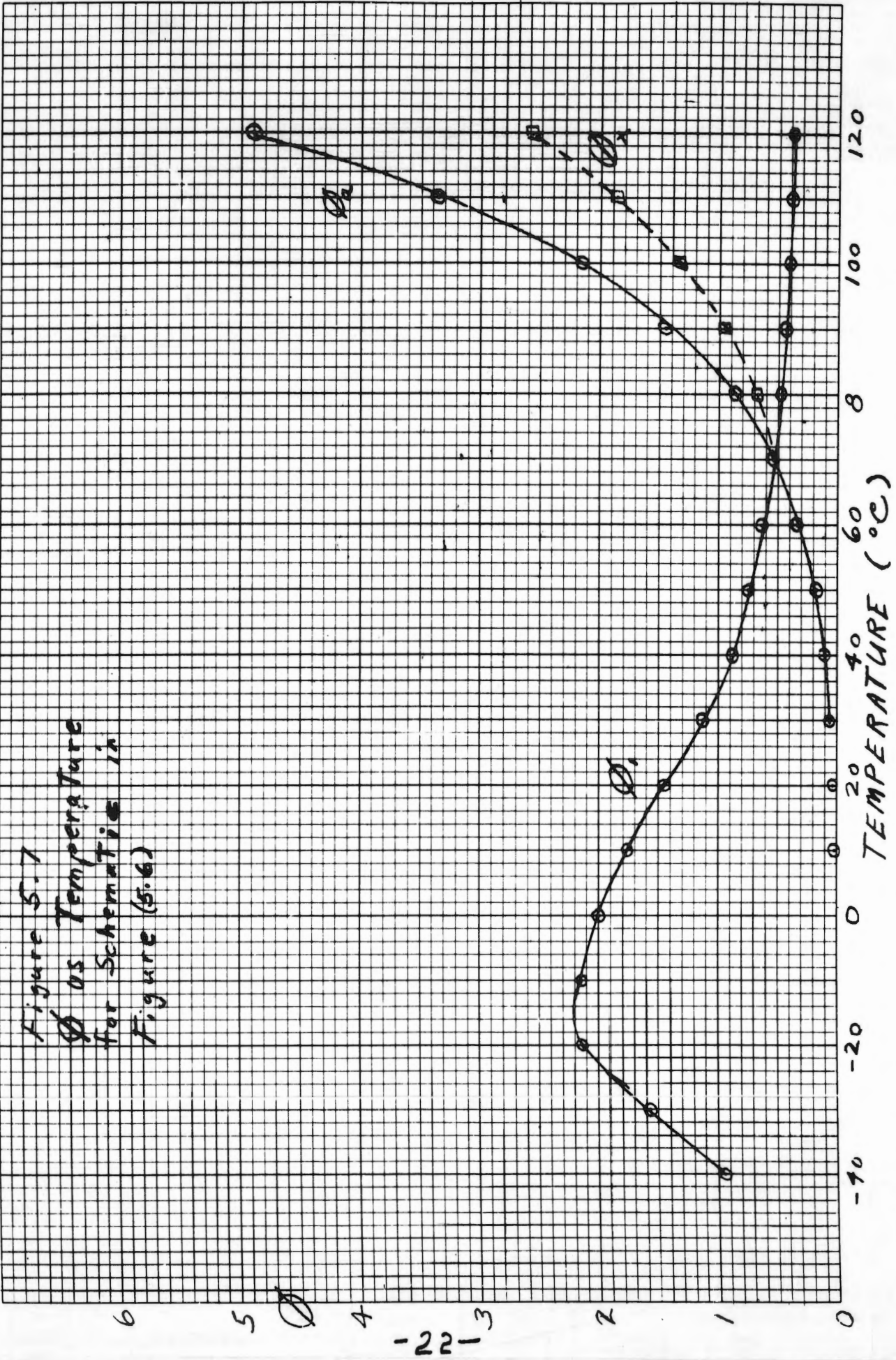


Figure 5.7
 ϕ as Temperature
 for Schematic in
 Figure (5.6)

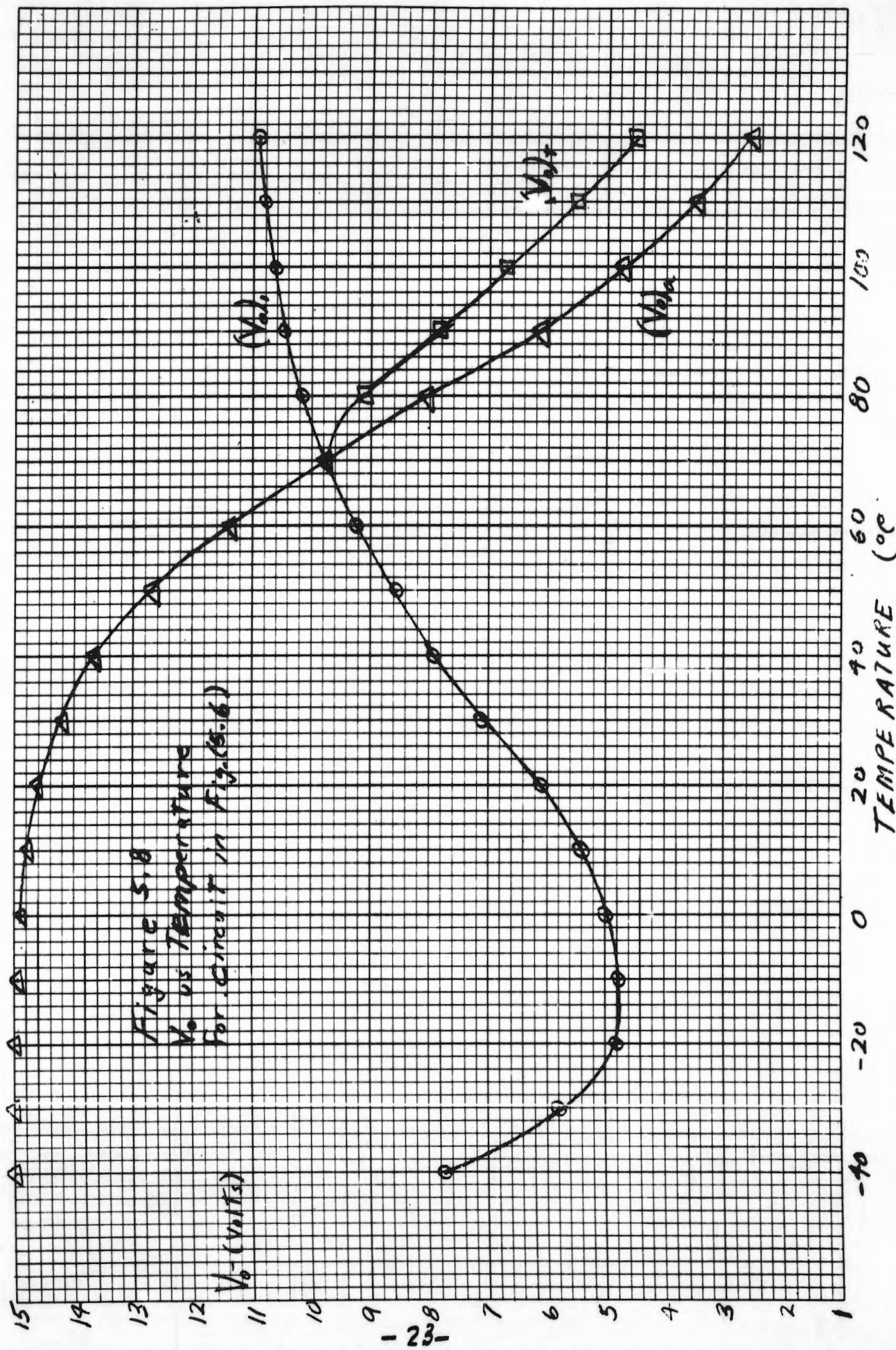


Figure 5.9
 V_o vs TEMPR. as a
 function of R_a

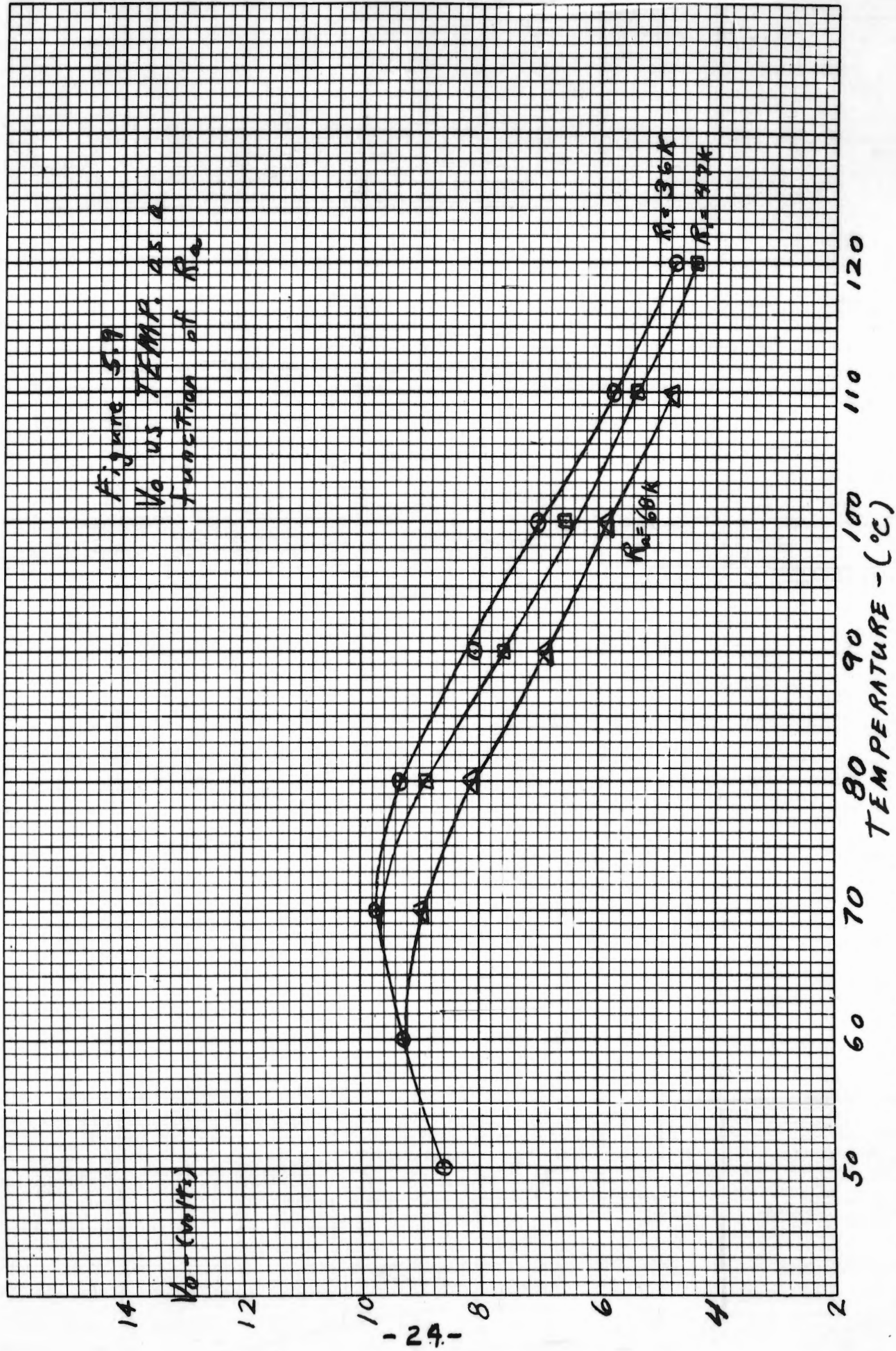
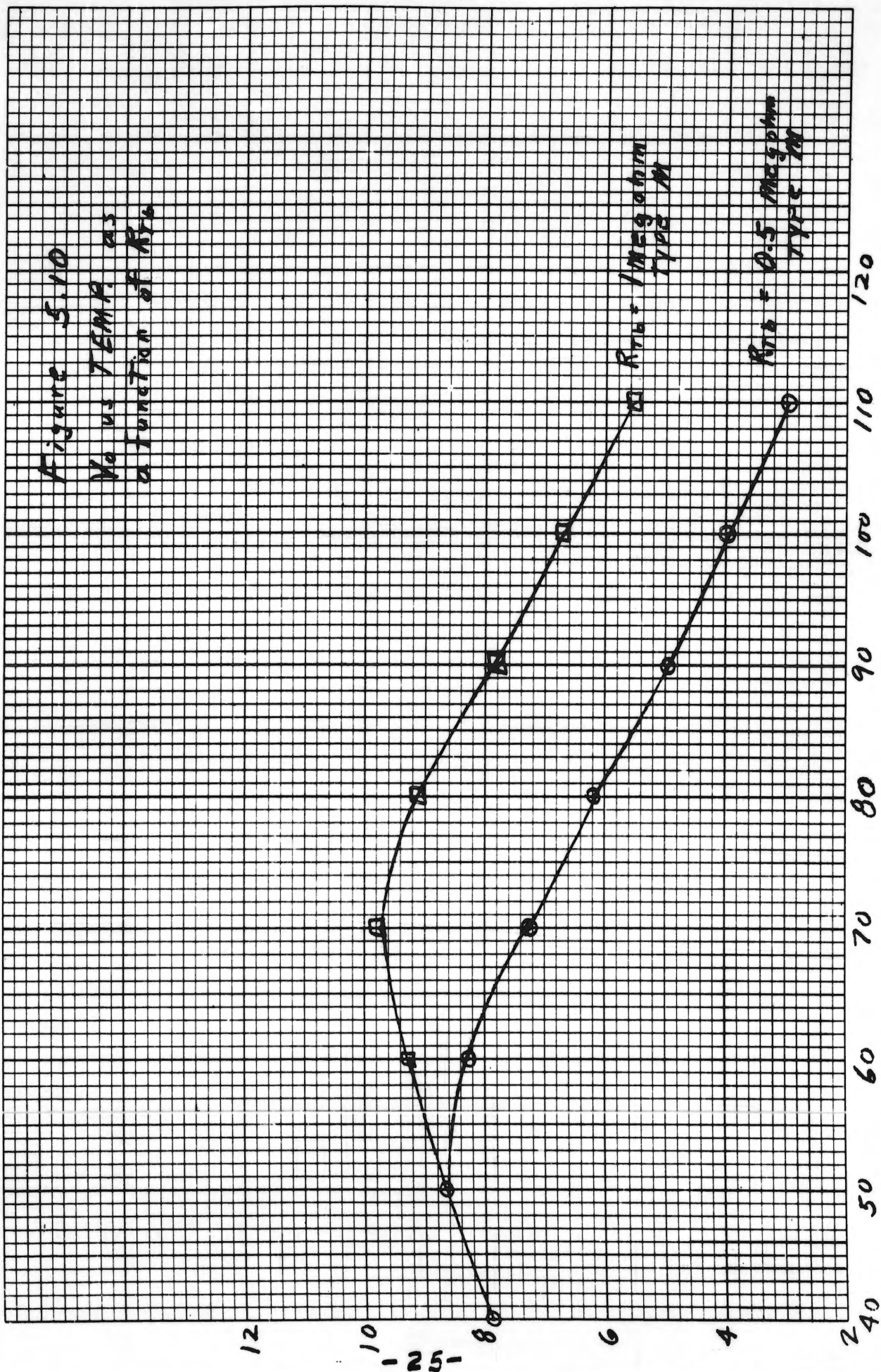


Figure 5.10

V_0 vs TEMPERATURE as a function of R_{T16}



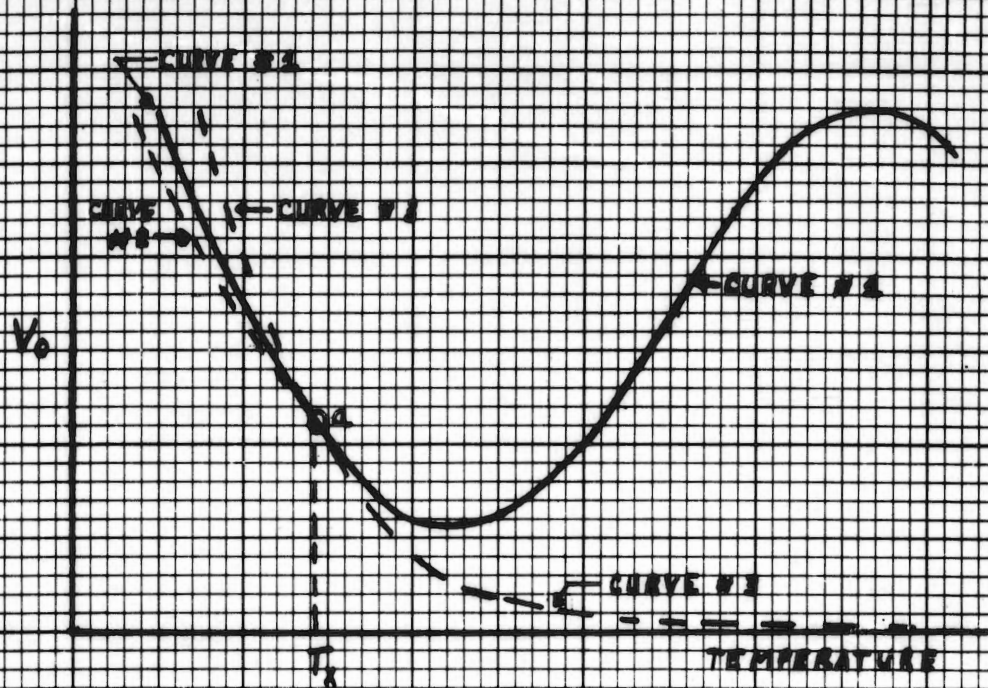
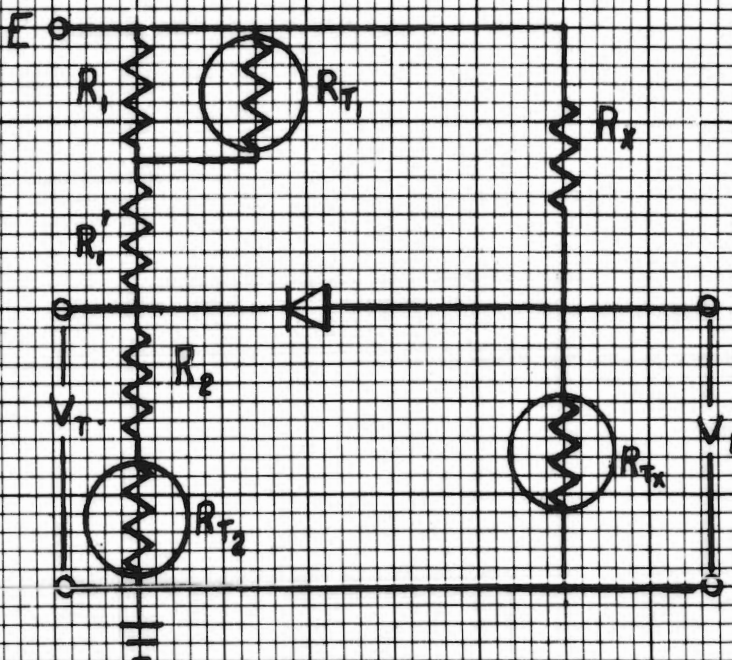


FIGURE 5.11



DIODE SWITCH CIRCUIT

FIGURE 5.12

Curve 2 is a possible V versus temperature curve that can be obtained from the network shown in Figure 5.4. The change in slope that is required is easily obtained at the upper turning point as can be seen. A different situation exists when the rate of change of the voltage versus temperature at the low temperature end is not great enough and a switch is used to increase it. R_{t_a} in Z_2 controls the rate of change for the low temperature end. The reason why the β of R_{t_a} cannot be increased to obtain the required increase in slope is that for some instances the large β thermistor needed to obtain the required rate of change for the -30°C to -40°C range is not needed and cannot be tolerated around the lower turning point. Also, physical limitations on the size of thermistors with high β values and R_0 's in the range of 1 K to 10 K, (which is usually what R_{t_1} is), are a problem. Curve 3 is the characteristic of V_1 in the circuit in Figure 5.12 with the diode disconnected. Curve 2 is the voltage V_0 characteristic with the diode removed, Curve 1 results when the diode is connected.

To obtain the required characteristic a high β for R_{t_x} is needed, which has the same problem as stated previously. Also, the transition of the diode from reverse bias to forward bias is relatively slow, because the two curves 1 and 3, have approximately the same slope. Therefore, a sharp change in slope will not occur when the diode conducts. The use of the diode switch for the low temperature end is restricted and is not always adequate to enable the correct slope to be obtained.

Use of the diode switch will enable lower angle crystals to be compensated much more readily. This can result in the use of the optimum crystal, with respect to total frequency deviation with temperature, for compensated oscillators. The main obstacle previously to the low angle crystal was the change in slope at the upper turning point. It must be determined by further tests whether the diode switch will become too complex for practical use or whether the determination of the components can be reduced to a straightforward approach.

6.1 Frequency Adjustment

One of the requirements placed on any oscillator that has a very precisely controlled frequency, is that its frequency be manually adjustable. This requirement is needed to take care of long term frequency drift due to the component and crystal aging and also due to permanent frequency changes due to environmental factors. The normal method of obtaining a frequency adjustment is to place a variable capacitor in a portion of the oscillator where a sufficient frequency change is obtainable. In a TCXO, the same approach to a frequency adjustment can be taken, but a number of problems present themselves. First, any change in capacitance in the TCXO that causes a change in frequency is changing the load capacitance of the crystal. Figure 6.1 is a plot of frequency, $\Delta f/f$, versus load capacitance for a crystal with $r = C_0/C_1$ ratio of 350.

In a TCXO the load capacitance of the crystal is made to vary as a function of temperature in such a manner that temperature compensation is afforded. In a typical oscillator the capacitance change versus temperature that is required may be as shown in Figure 6.2.

Equation 6.1 is the equation for the change in frequency due to a change in load capacitance. Equation 6.2 is the derivative of $\Delta f/f$ with respect to C_x .

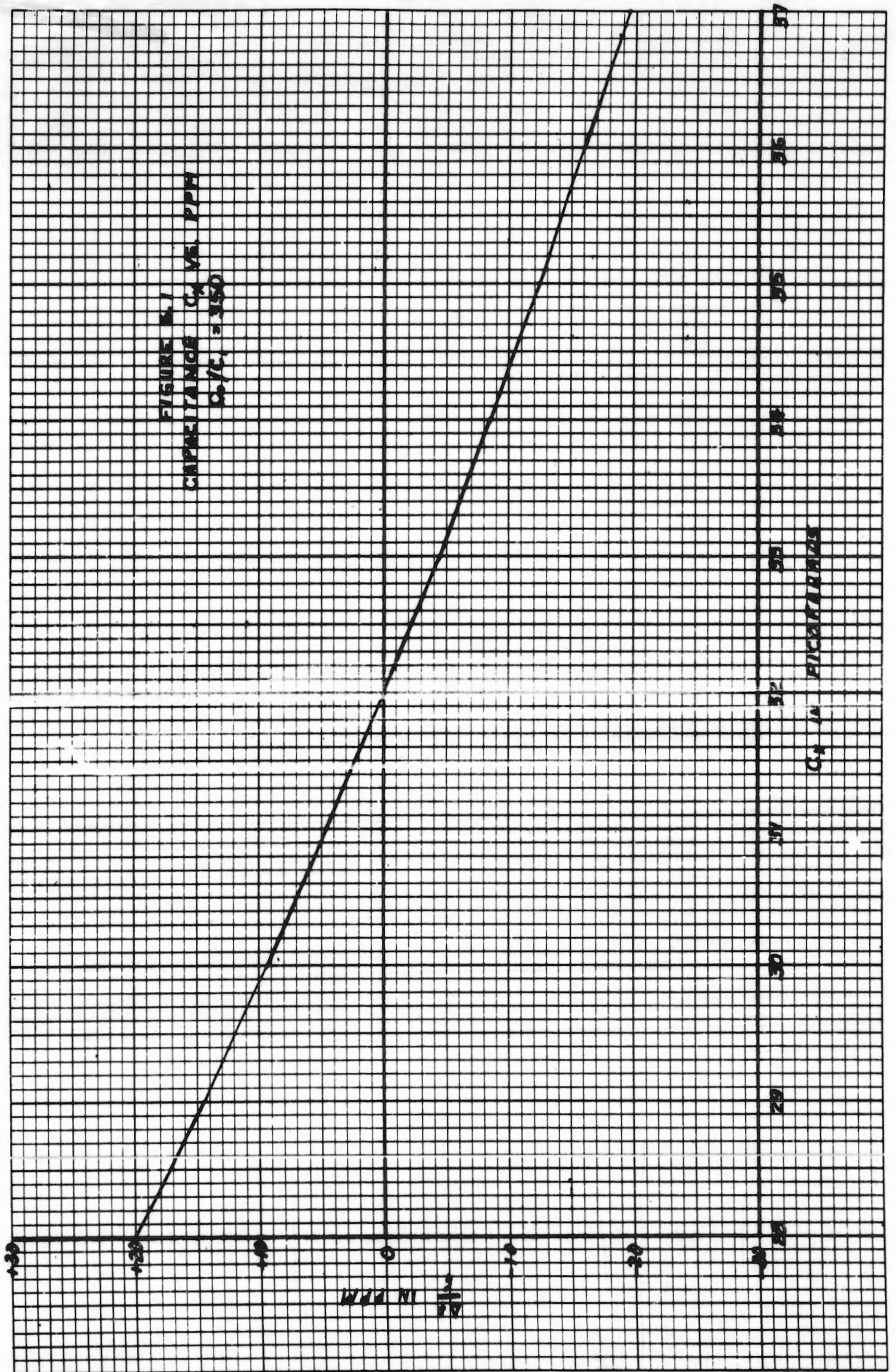
Equation 1

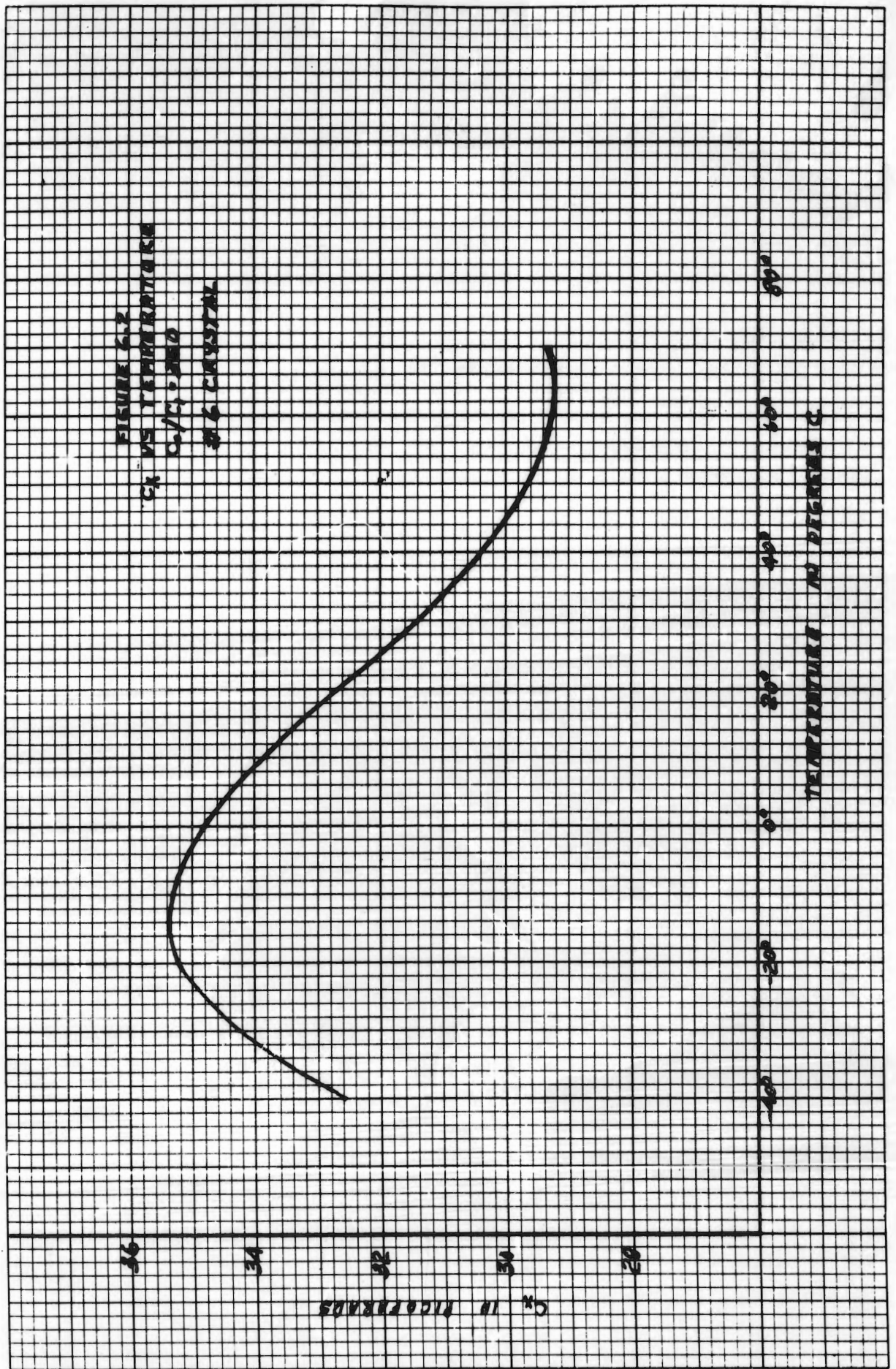
$$\Delta f/f = p = -M + \frac{C_0 \times 10^6}{2r (C_0 + C_x)}$$

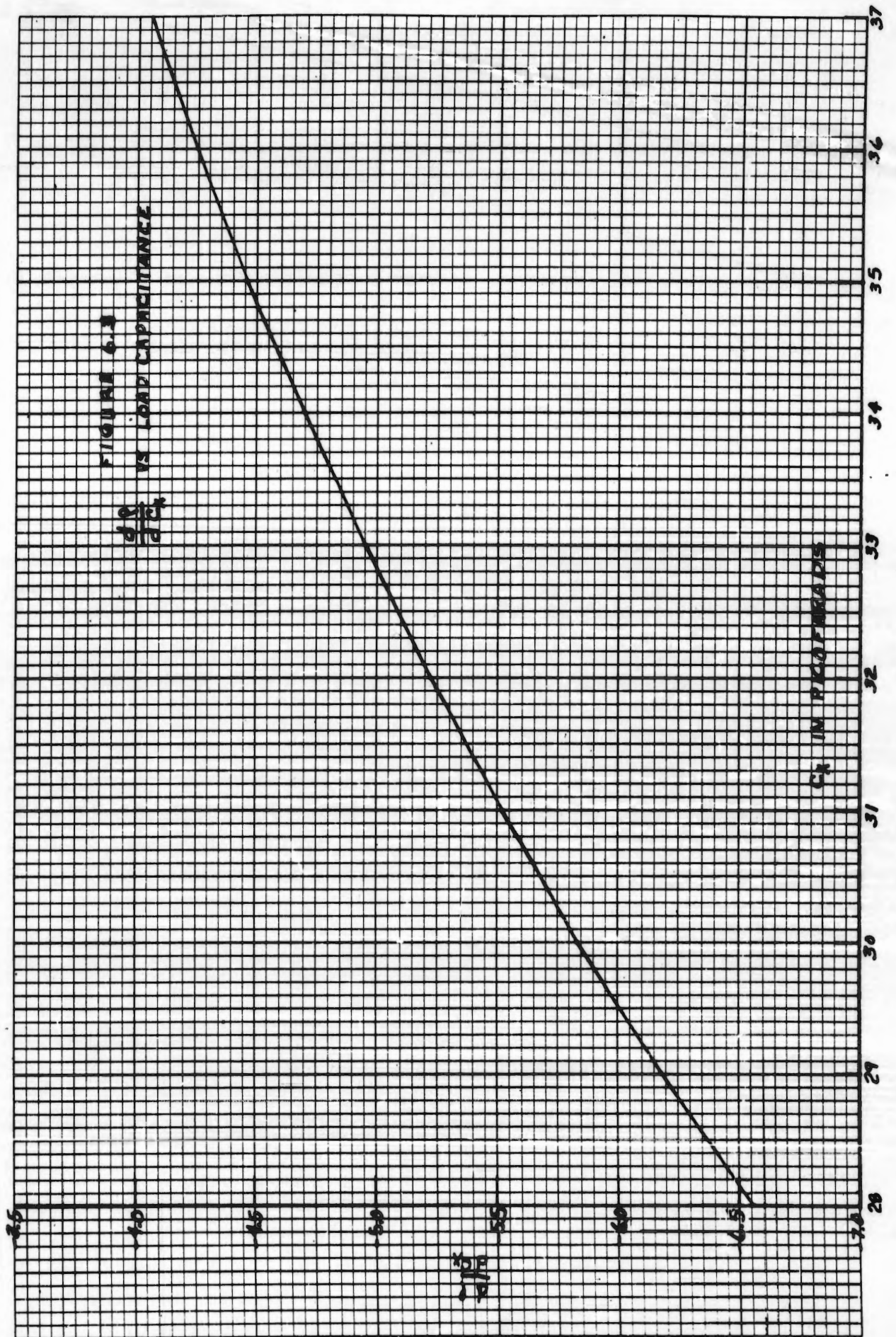
Equation 2

$$\frac{dp}{d C_x} = - \frac{C_0 \times 10^6}{2r (C_0 + C_x)^2}$$

Figure 6.3 is a plot of $dp/d C_x$ versus C_x . As can be seen, the rate of change of frequency with a change in C_x decreases as C_x becomes larger. This fact is what causes the difficulty when a TCXO is to be tuned. First, assume that the tuning capacitor C_x is across the crystal. This means C_x will change exactly the same magnitude as C_x .







The change in C_x with temperature will not vary due to the tuning capacitor, only the magnitude will vary. But as the magnitude of C_x varies, the rate of change of $\Delta f/f$ versus C_x also varies. Therefore, if C_x is changed by 1 pf, the slope of frequency, $\Delta f/f$ versus temperature will not be zero, but will be changed by the amount indicated by Equation 2. It is obvious that a tuning capacitor cannot be placed across the crystal in a TCXO, without affecting the change in frequency for a given change in C_x .

One other place where the tuning capacitor can be placed is across the TCXO and varicap. Changing the capacitance of the tuning capacitor does not result in a one to one change in load capacitance, rather the load capacitance is changed as shown by Equation 3.

Equation 3

$$C_x = \frac{(C_c + C_k) (C_v)}{(C_c + C_k) + C_v}$$

The variable capacitance, C_k , appears as part of the circuit capacitance, C_c . The same effect occurs when C_k is varied in this position as it did when it was across the crystal, that is that the operating point on the crystal $\Delta f/f$ versus C_x curve has to be changed to result in a change in frequency. This results in a change in slope of the pullability curve of the oscillator. One other effect occurs, and that is that the effect of C_v on C_x is also changed.

If C_k is changed in such a manner that frequency decreases, then its effect must be to increase C_x . C_k must therefore increase. As C_k increases, the TCXO crystal is operating on a lower slope point of its $\Delta f/f$ versus C_x characteristics. But at the same time, as C_k increases, the effect of C_v on C_x increases. As C_k becomes larger, $d C_x/d C_v$ becomes greater. So as $d \frac{\Delta f/f}{d C_x}$ decreases, $d C_x/d C_v$ increases, resulting in a partial cancellation of the effect of changing C_k .

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Equation 4

$$\frac{d C_x}{d C_v} = \frac{C_c^2 + 2C_c C_k + C_k^2}{(C_c + C_k + C_v)^2}$$

An analysis of the circuit shown in Figure 6.4 has been done to determine if no effect on the slope of the $\Delta f/f$ versus voltage curves due to changing the absolute frequency can be obtained by selecting the appropriate component values. Equation 5 is the derivative of C_x with respect to V .

Equation 5

$$\frac{d C_x}{d V} = \frac{d \left(\frac{C_c C_v}{C_c + C_v} \right)}{d V} = C_c \frac{d \left(\frac{K/V^{1/2}}{C_c + K/V^{1/2}} \right)}{d V} = \frac{C_c^2 K V^{-1/2}}{2 (C_c V^{1/2} + K)^2}$$

$$C_v = \frac{K}{V^{1/2}}$$

Equation 6 is the change in frequency due to a change in varicap voltage, obtained from Equations 2 and 5.

Equation 6

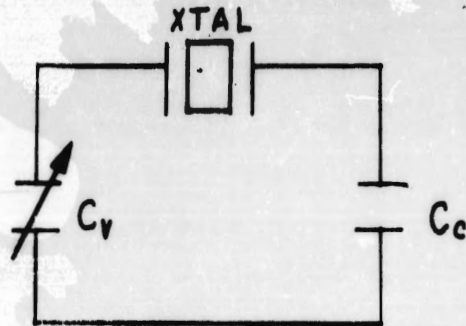
$$\frac{d \rho}{d V} = \left(\frac{d C_x}{d V} \right) \left(\frac{d \rho}{d C_x} \right) = \left(- \frac{K V^{-1/2} C_c^2}{2 (C_c V^{1/2} + K)^2} \right) \left(- \frac{C_o \times 10^6}{2r (C_o + C_x)^2} \right) = \frac{N C_o C_c^2 \times 10^6}{4Vr (C_o C_c + C_o N + C_c N)^2}$$

where $N = K V^{-1/2} = C_v$

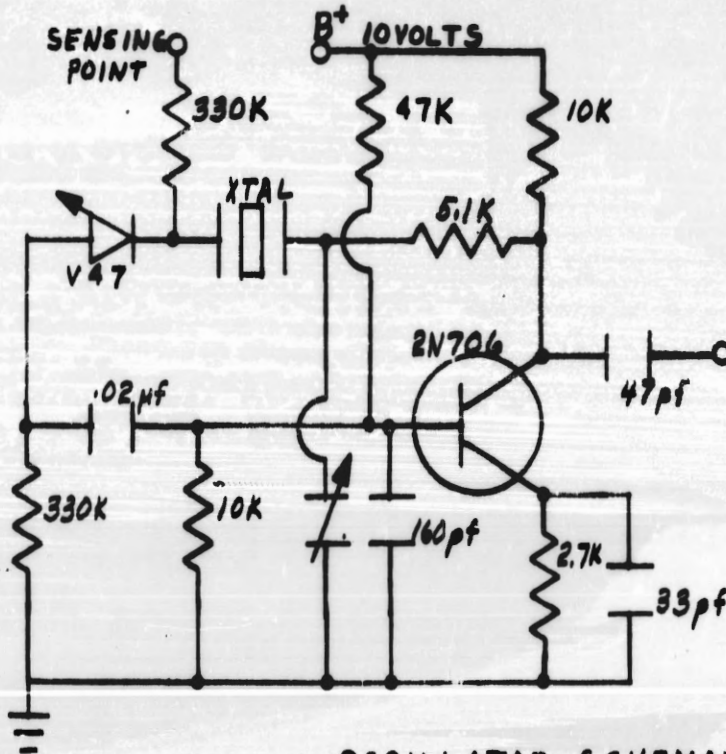
By inspecting Equation 1, where $C_x = \frac{C_c C_v}{C_c + C_v}$ it is obvious that a change in absolute frequency can be obtained by changing either C_c or C_o or both. However, Equation 6 indicates that a change in only one of these values will effect the slope of the $\Delta f/f$ versus voltage curves.

Equation 7

$$\text{Let } \frac{d \rho}{d V} = S$$



CRYSTAL AND LOAD CAPACITANCE
 FIGURE 6.4



OSCILLATOR SCHEMATIC
 FIGURE 6.5

Thus by solving Equation 7 for either C_c or C_o , the value of the dependent variable required to maintain a constant slope, S , as a result of changing the independent variable can be determined.

Equation 8

$$\frac{C_c^2}{(C_o C_c + C_o N + C_c N)^2} = A \quad \text{where } A = \frac{4SV}{C_1 N} \times 10^{-6}$$

Equation 9

$$C_o = \frac{-C_c (N \pm \sqrt{1/A})}{C_c + N}$$

Equation 10

$$C_c = \frac{-C_o N \sqrt{A}}{\sqrt{A} (C_o + N) \pm 1}$$

Because C_o and C_c can only be positive the two equations must be,

Equation 11

$$C_o = \frac{-C_c (N - \sqrt{1/A})}{C_c + N}$$

Equation 12

$$C_c = \frac{-C_o N \sqrt{A}}{\sqrt{A} (C_o + N) - 1}$$

Thus for a given range of N , say 40 pf to 60 pf, the relationship for C_c and C_o is determined.

For any given circuit design, the parameters C_o , C_c , and N or the range of N can be optimized. The actual optimum point may not be realistic, but if the circuit is initially designed towards the optimum values the effect of tuning can be reduced.

The circuit shown in Figure 6.5 was used to determine the effect of changing the collector to emitter capacitance, C_c . The $\Delta f/f$ versus V curve was

plotted with $C_0 = 160$ pf. Then C_0 was increased so that a 26 ppm shift was obtained. Figure 6.6 shows the two $\Delta f/f$ versus V curves obtained. The difference in the total frequency change from 1 to 7 volts was 18/5 ppm, while a total change of approximately 80 ppm was obtained, representing a 4.5% change for a 26 ppm change in absolute frequency and a 6 volt change in voltage. A figure of merit can be defined as the average percentage change in frequency for a given voltage and absolute frequency change and is given by Equation 13.

Equation 13
$$\Delta \rho_1 = \sigma V_0 \rho_3 \quad \text{where } \sigma = \frac{|\Delta \rho_1|_{\max}}{V_{0\max} \rho_{3\max}}$$

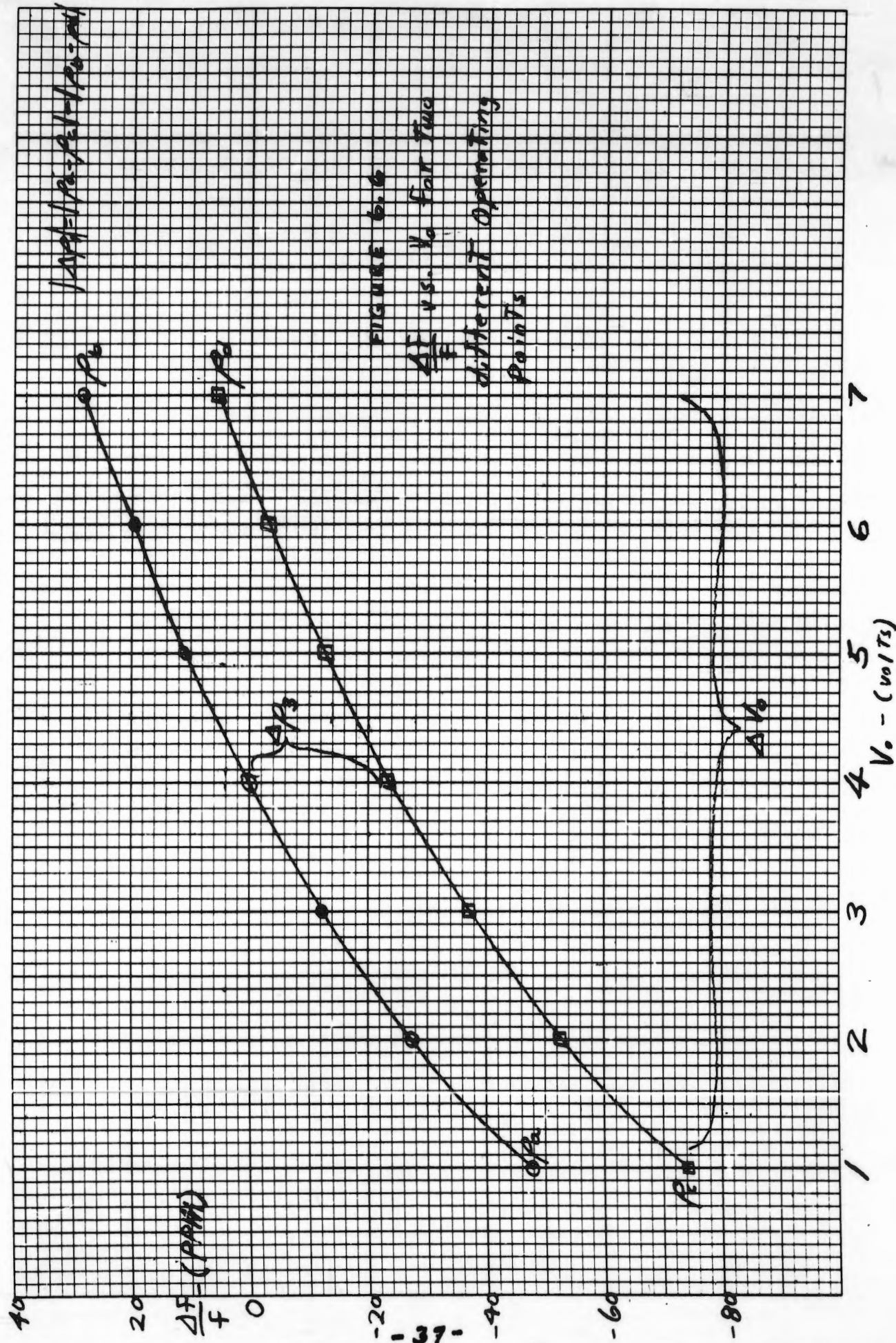
$\Delta \rho_1$ is the change in frequency caused by a change in slope due to changing the absolute frequency an amount ρ_3 . As σ becomes smaller the effect of changing the absolute frequency becomes less. For Figure 6.6:

$$\sigma = \frac{4 \text{ ppm}}{(6 \text{ volts})(26 \text{ ppm})} = 2.56 \times 10^{-2} \frac{\text{ppm}}{\text{V-ppm}}$$

So for: $V_0 = 2$ volts, $\rho_3 = 10$ ppm

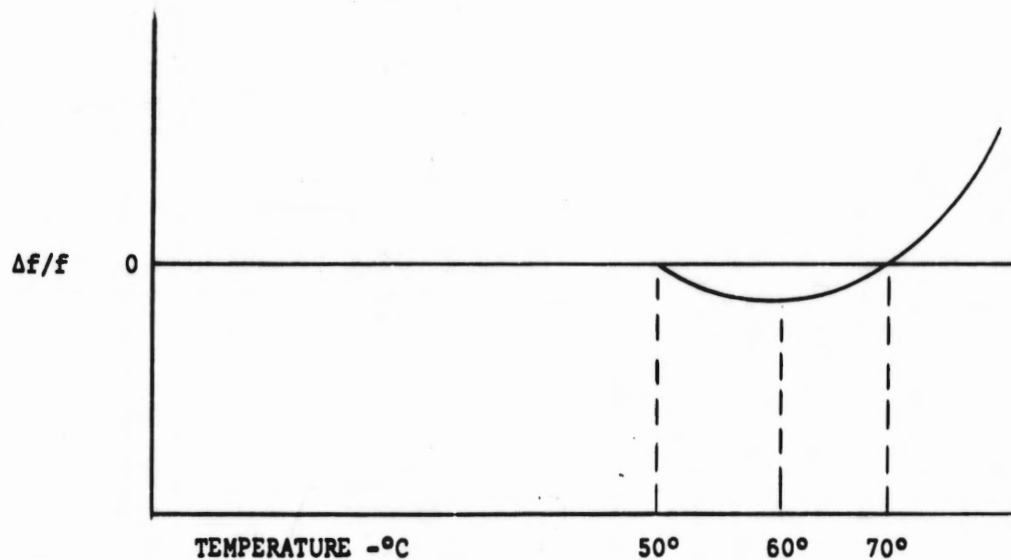
$$\Delta \rho_1 = (2.5 \times 10^{-2})(2)(10) = 50 \times 10^{-2} = 0.5 \text{ ppm}$$

If a change in voltage of two volts is desired and it is desired to have a 10 ppm absolute frequency adjustment range, then the difference between the two $\Delta f/f$ versus V curves will be 0.5 ppm.



7.1 Crystal Characteristics

Crystal frequency versus temperature characteristics are being investigated more thoroughly. In recent units being designed for stabilities with temperature in the 0.5 ppm to 0.1 ppm region, discrepancies have occurred that were not anticipated. Temperature compensation at the upper turning point is where the major difficulties have arisen. Figure 7.1 illustrates the result that may be obtained at the upper turning point.



TCXO $\Delta f/f$ Versus Temperature Curve

Figure 7.1

Figure 7.2 illustrates the assumed characteristics at the upper turning point temperature.

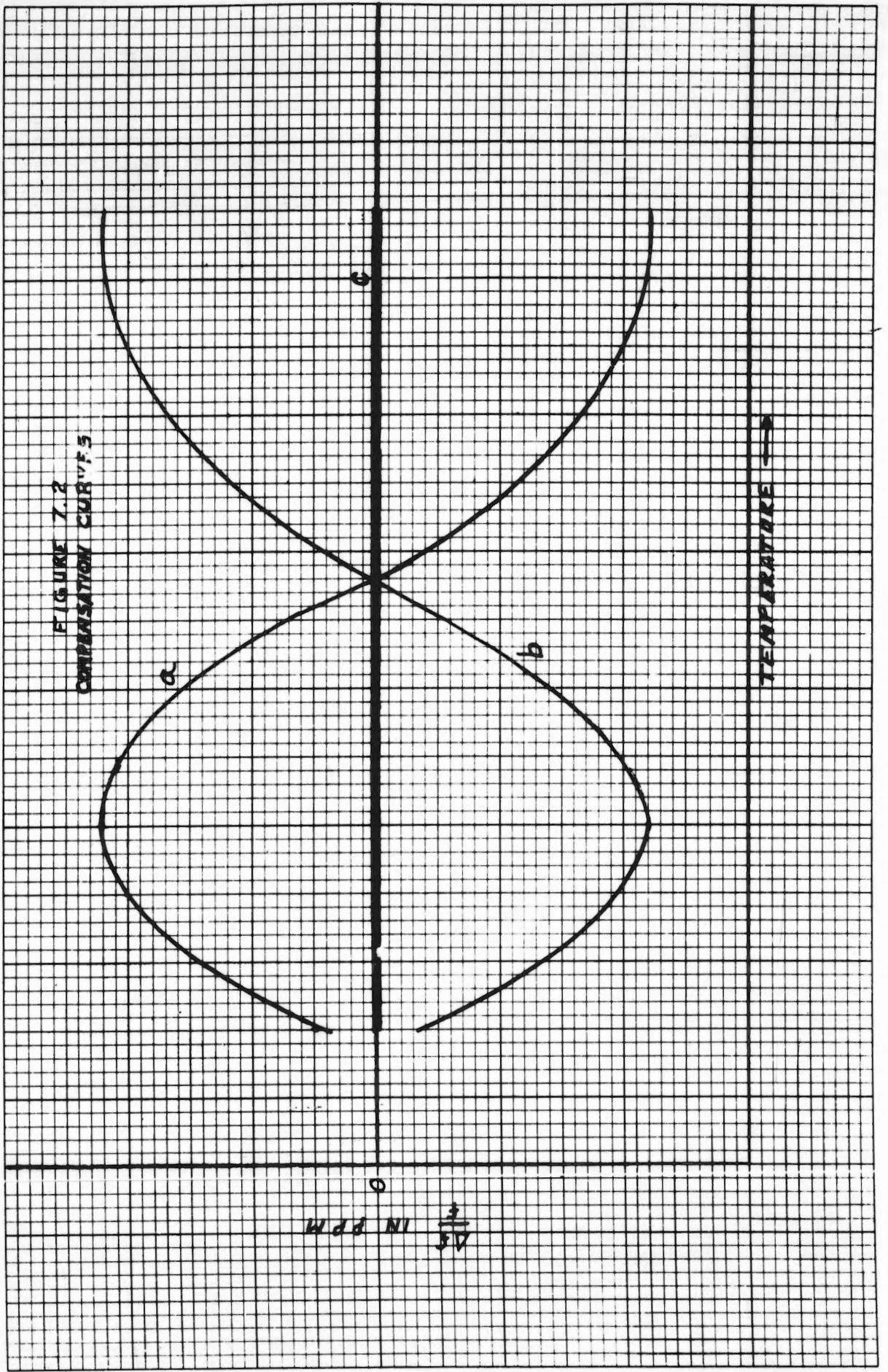


FIGURE 7.2
COMPARISON CURVES

Curve "a" is the crystal $\Delta f/f$ versus temperature curve, "b" is the compensation circuit characteristics, and curve "c" is the resultant TCXO $\Delta f/f$ versus temperature curve. The characteristics of actual TCXO's do not fully agree with the assumption. After examining the curves in Figure 7.1 and Figure 7.2, two explanations were formed that will explain the deviation in the actual TCXO characteristics and the calculated characteristics. One, the compensation network can have a non-linearity or, two, the crystal curve can have a non-linearity. Figure 7.3 illustrates what must happen to the compensation characteristic if the curve shown in Figure 7.1 is to be obtained. The $\Delta f/f$ curve produced by the compensation must be changing at a slower rate than the crystal curve. This is a possibility and has been observed in some of the experimental TCXO compensation networks. The diode switch will help to eliminate this effect of the compensation network.

The other case, where the crystal has a non-linearity can cause the same effect. Figure 7.4 shows a crystal curve that was measured around the upper turning point. As can be seen the curve becomes very flat for a small temperature range. With this type of non-linearity, a compensation curve that was obtained by measurements at every ten degrees would possibly not detect the non-linearity. This would result in an error in the resultant $\Delta f/f$ versus temperature curve of the TCXO. More investigation into the crystal characteristics around the upper turning point is being done to see if the curve for the crystal shown in Figure 7.4 occurs in other crystals.

Figure 7.3

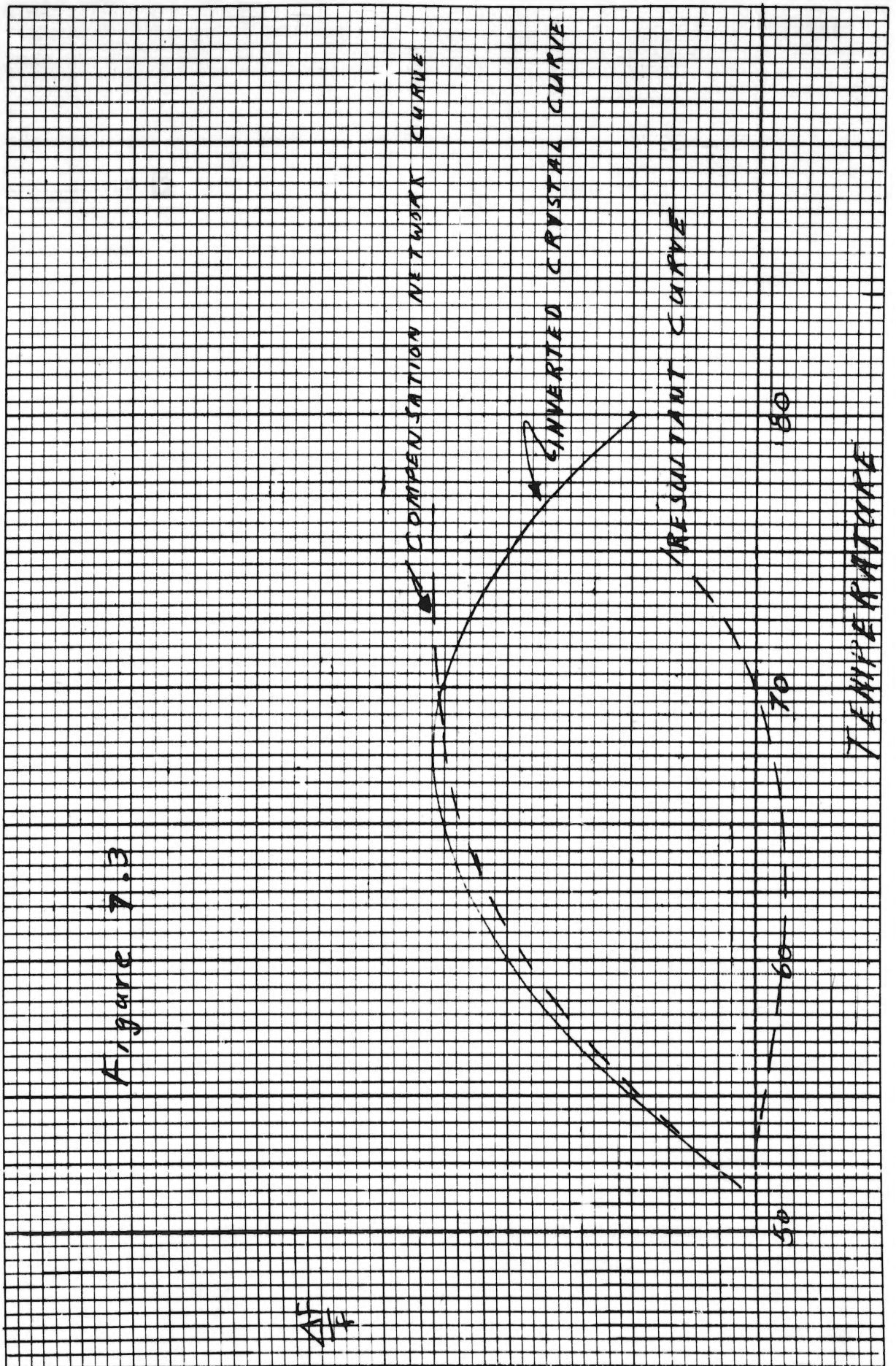
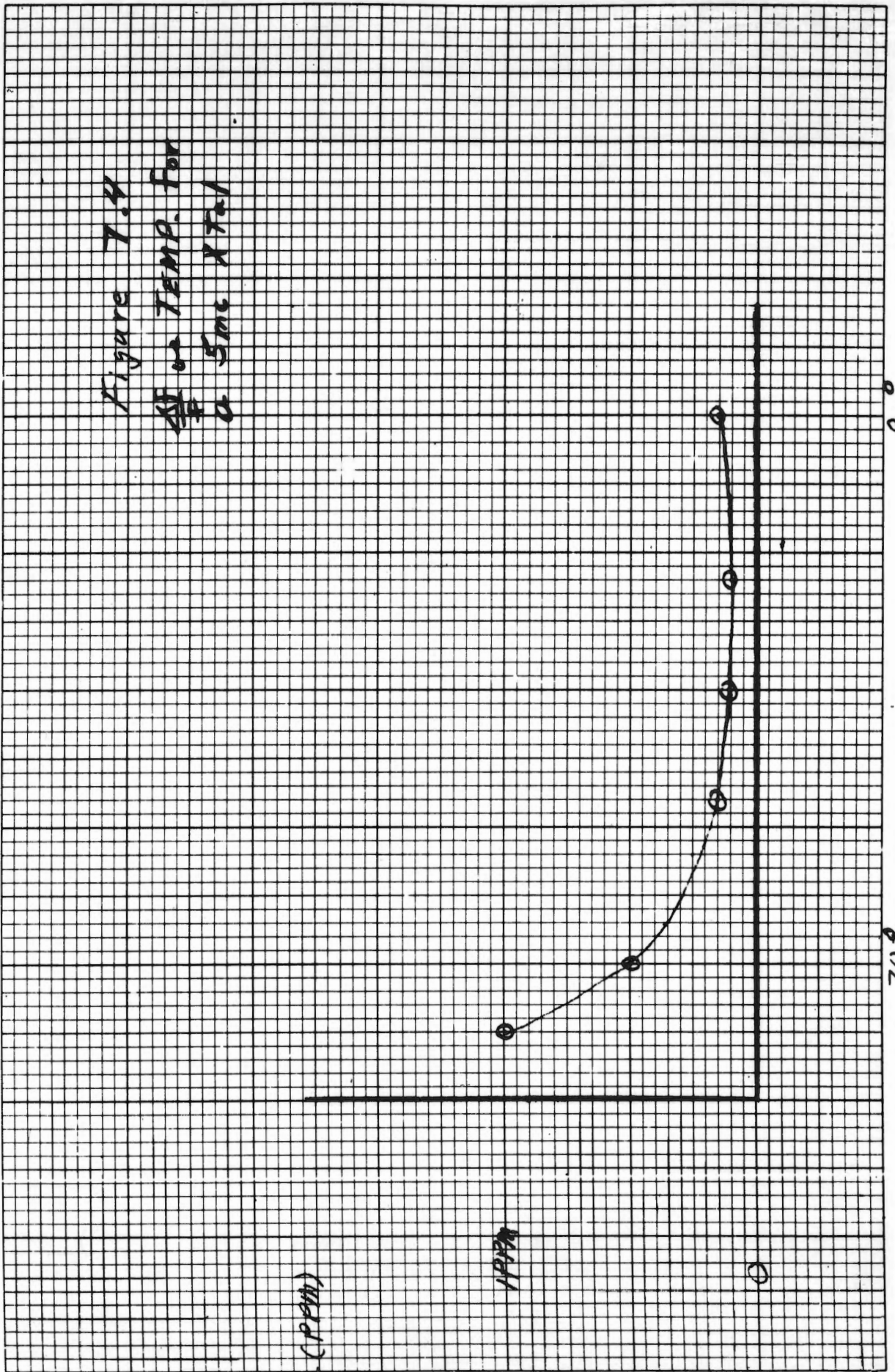


Figure 7.4
 ΔH vs TEMP. for
 a 5mc Xtal



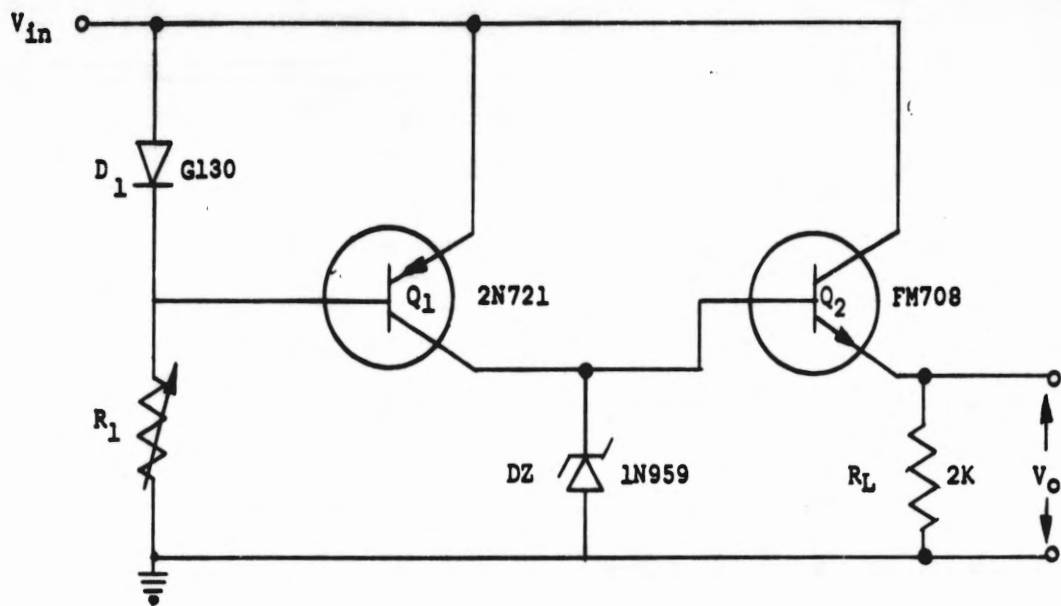
8.1 Voltage Regulation

Because the TCXO is, in a sense, a voltage controlled device, the variations in the supply voltage cause changes in the frequency. Many practical applications for a TCXO require that it be operated from a voltage supply that has as much as $\pm 15\%$ change. This necessitates that a voltage regulator be included in the TCXO package, to reduce the variation of the supply voltage for the TCXO.

If an overall sensitivity to supply voltage variation is of the order of $+1$ ppm/volt, then a 10 millivolt change will cause a deviation of 0.01 ppm. This voltage stability is required where compensation to parts in 10^{-7} is required. With a supply voltage of 10 volts, a 10 millivolt change requires 0.1% regulation; with a 20 volt supply voltage, 0.05% regulation is required.

To obtain this regulation with very low power consumption has been a problem. Maintaining 0.1% regulation with temperature and voltage variation requires that a temperature compensated zener diode be used which typically will require 75 milliwatts or more. This is not realistic in view of the objectives of this study which is 50 milliwatts for the entire TCXO.

Therefore, low power consumption voltage regulation circuits have been investigated. The best one to date is that shown in Figure 8.1. Diode D_1 , resistor R_1 and transistor Q_1 are used to obtain a constant current bias for the zener diode, D_Z . This constant current bias holds the zener voltage relatively constant and is not affected to any great extent by input voltage variations. Transistor Q_2 and zener D_Z complete the voltage regulator circuit. Transistor Q_2 is used to allow a small base current to control the larger emitter load current.



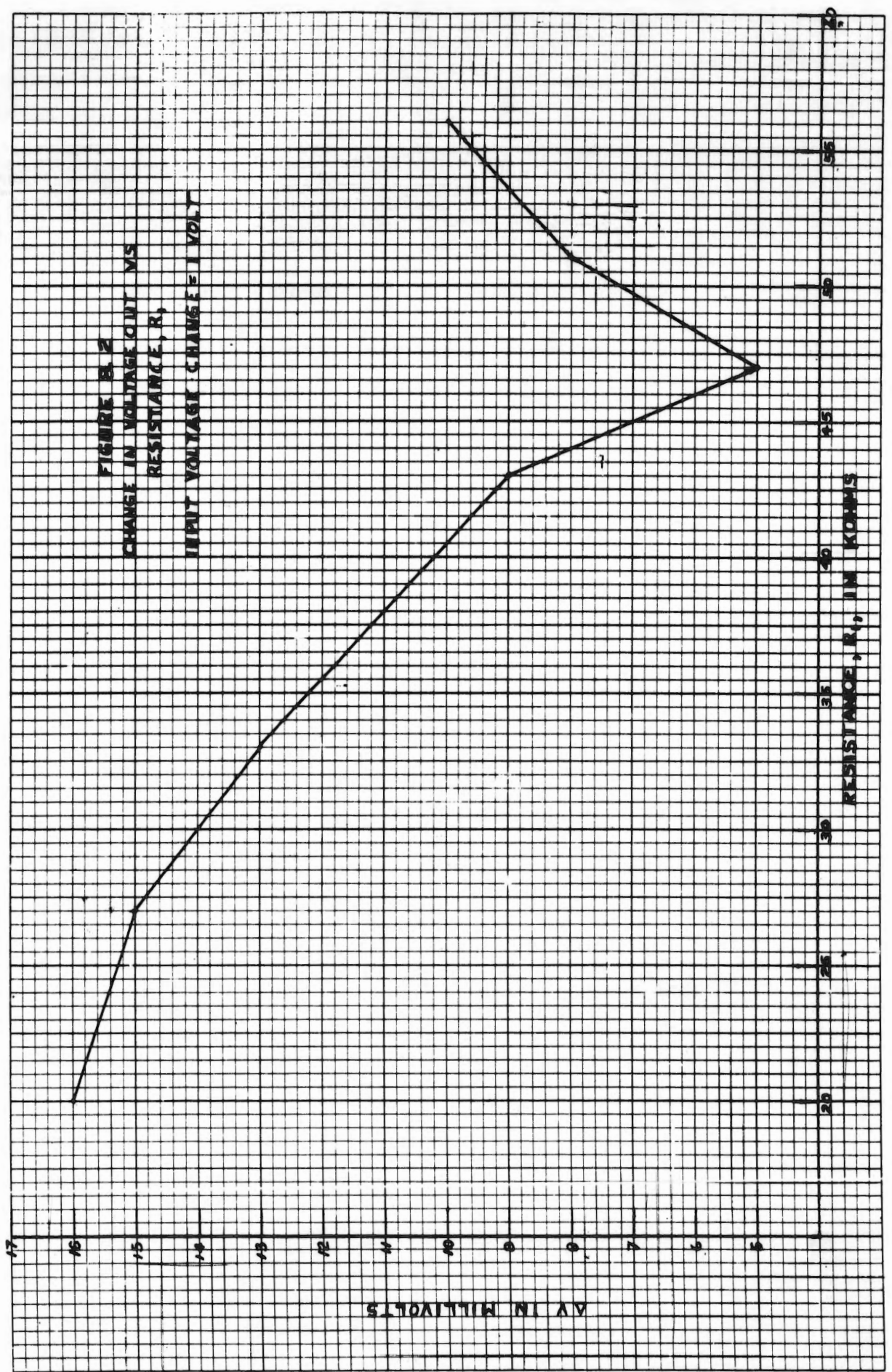
Voltage Regulator

Figure 8.1

This regulator draws about 8 milliwatts. The following curves illustrate some of the characteristics of this regulator. The critical components are the diode D_1 and the resistor R_1 . The characteristics of the diode must be such that it matches the characteristics of the emitter base junction of Q_1 . Resistor R_1 controls the current through Q_1 and D_Z . It must be selected because of the β tolerance from transistor to transistor.

The following graphs show the characteristics of a number of voltage regulator circuits that were tested.

Figure 8.1 is the schematic of the regulator used for the results shown in Figures 8.2 and 8.3. Figure 8.2 and 8.3 shows the regulation of the output voltage versus resistance R_1 as a function of input voltage for two different regulators.



AV IN MILLIVOLTS

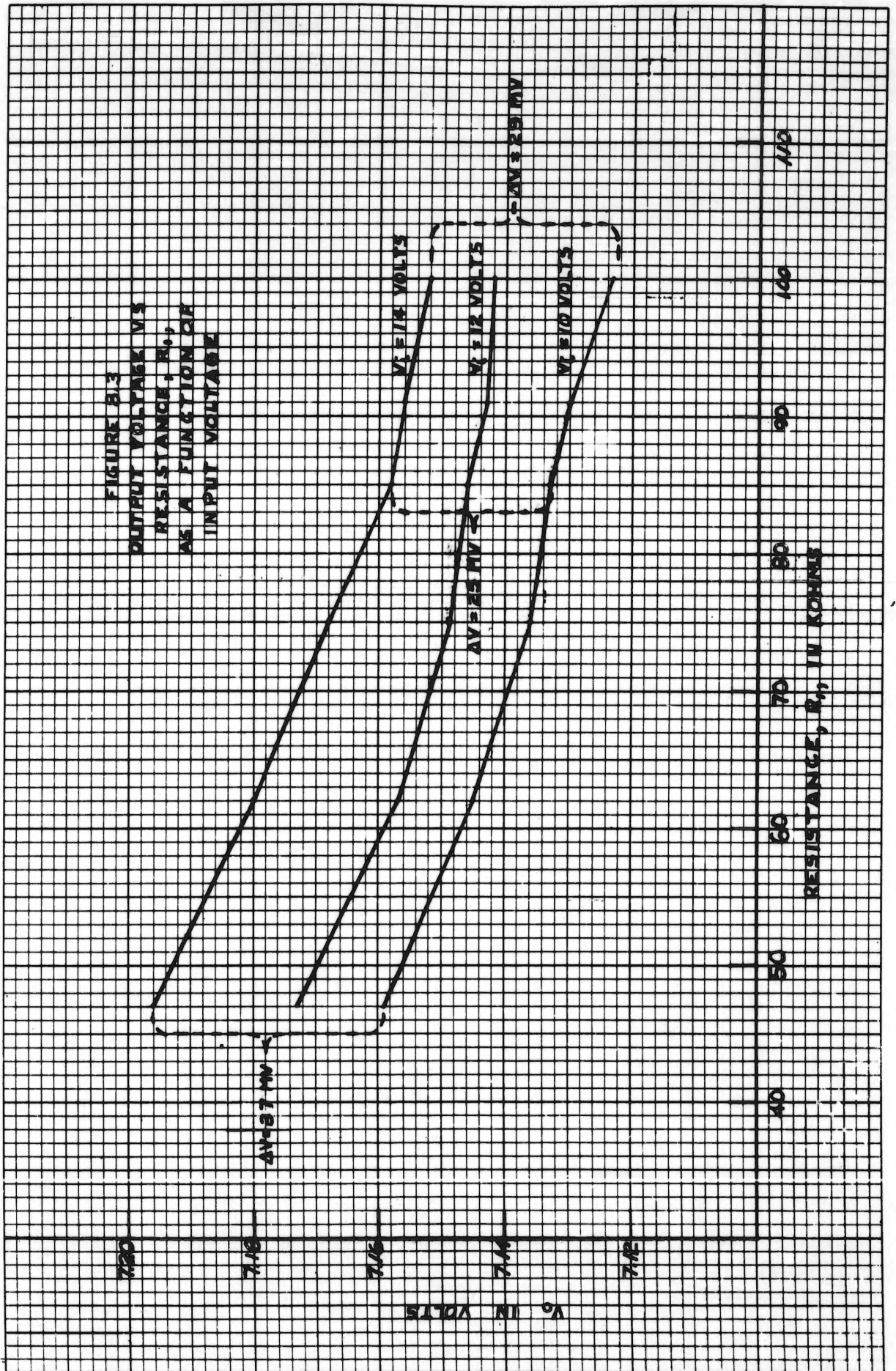
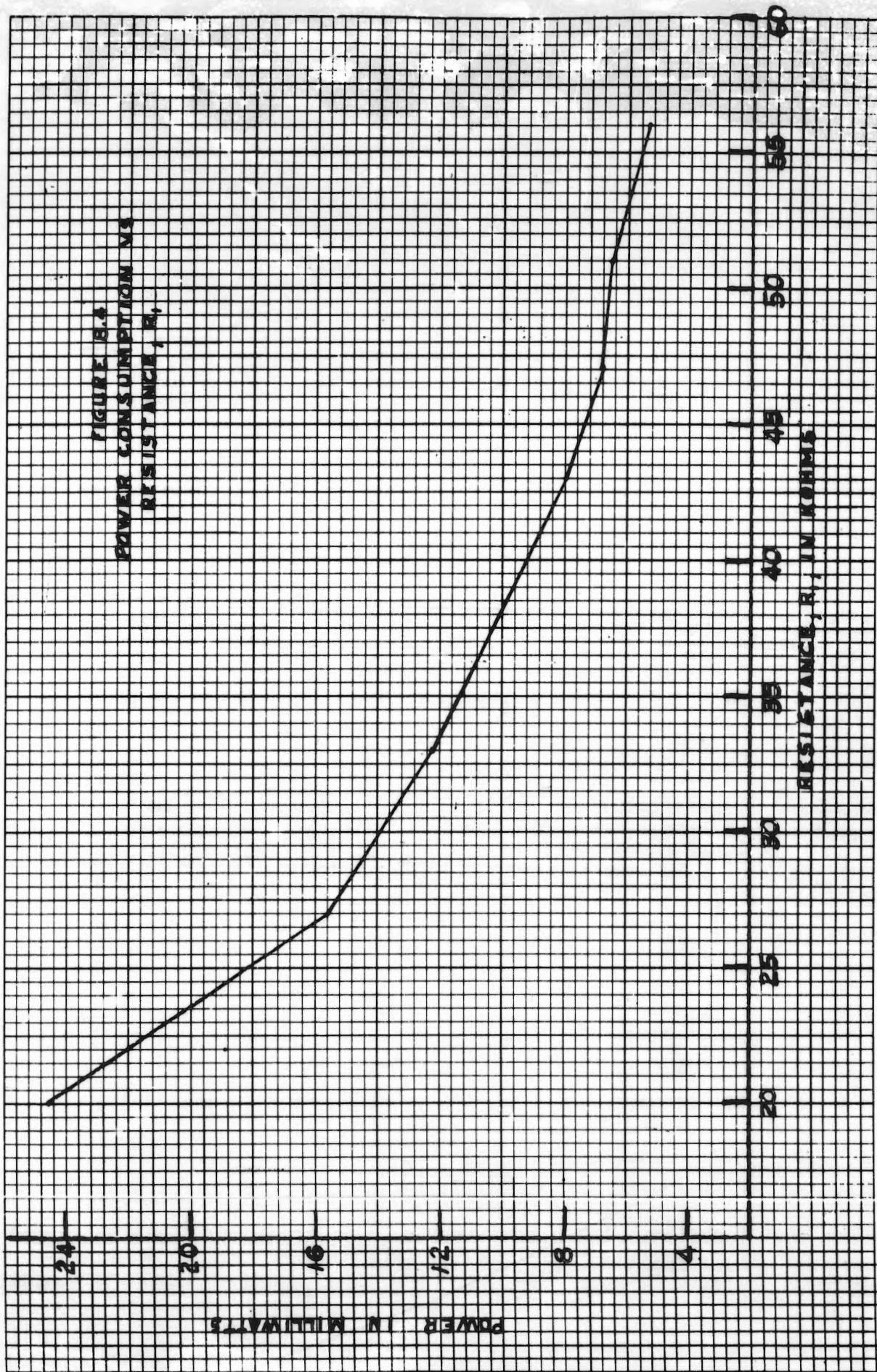


Figure 8.4 and 8.5 shows the power consumed by the regulator versus R_1 . The circuits shown were being optimized for the power consumed rather than the voltage regulation. By using zeners with better characteristics at low currents, better regulation can be obtained.



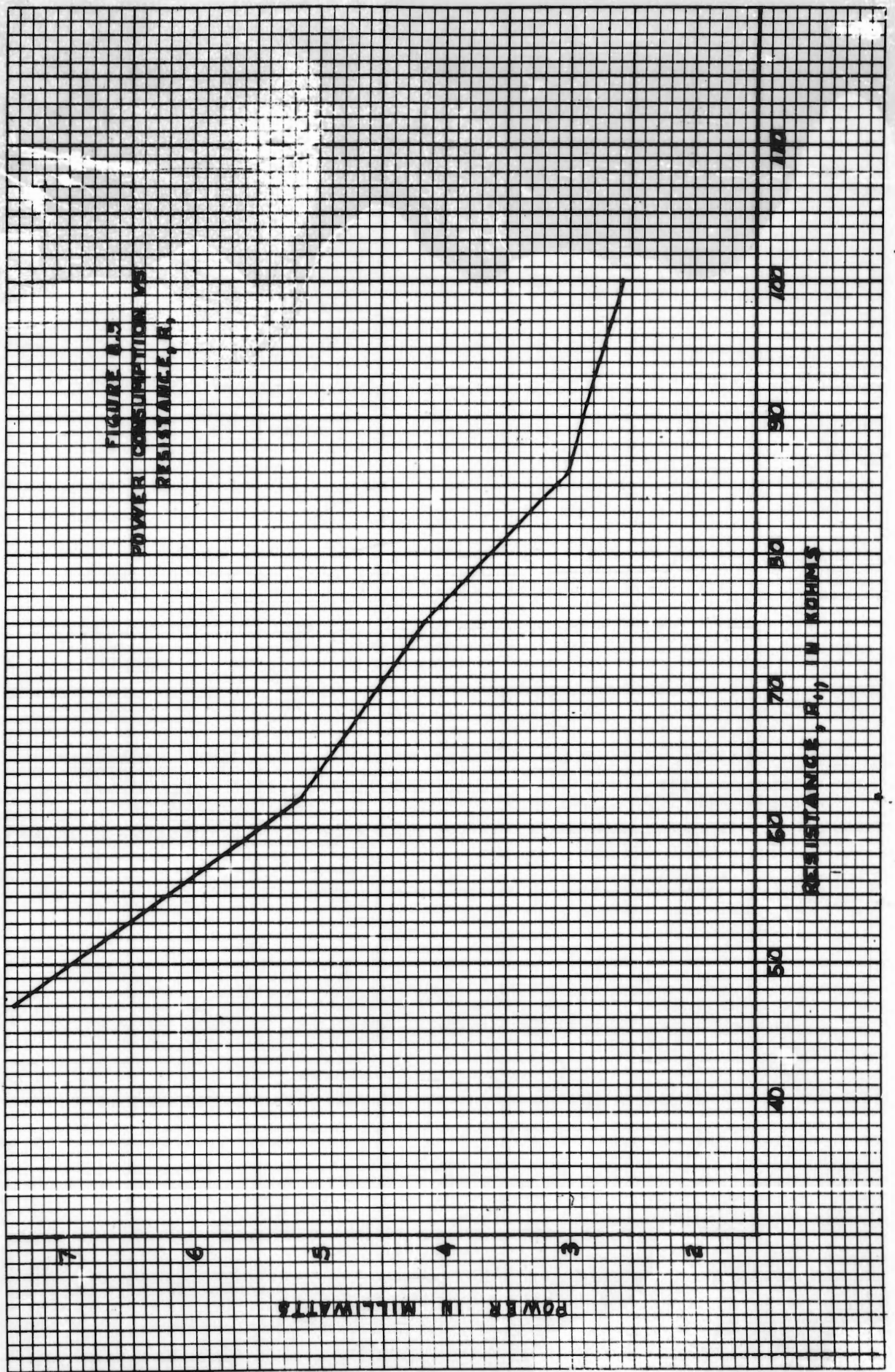


FIGURE A-3
POWER CONSUMPTION VS
RESISTANCE, R.

POWER IN MILLIWATTS

RESISTANCE, (R), IN KOHMS

9.1 Conclusions

The ability to generate the required voltage versus temperature curve for compensation will be increased by the use of the diode switch. The diode switch provides the right characteristics for the generation of an S-shaped voltage versus temperature curve, but for close tolerance compensation the exact network configuration will have to be determined very carefully.

The problem of frequency adjustment appears to be difficult, but not impossible to overcome. Examination of various schemes to use for frequency adjustment should result in a method that has little affect on compensation.

The presence of non-linearities in the crystal characteristics may or may not be a problem. If further studies indicate that non-linearities are frequent, then a method of easily detecting these must be devised and used in the selection of crystals for compensation purposes.

The design of a TCXO to fit in a 0.6" x 0.7" x 1.5" configuration appears to be feasible. The most difficult problem is obtaining extremely small components with the required stabilities.

10.1 Program for Next Quarter

The diode switch investigation will continue. Refinements will be made in the circuitry and method of computation as they are required.

Crystal characteristics will be studied more thoroughly.

The design of the Type I and Type III TCXO's will be completed.

Different methods of frequency adjustment will be studied to determine a method that will result in the minimum effect on compensation.

The compensation procedure outlined previously will be revised in an effort to standardize the TCXO components.

11.1 Personnel Associated with the Project

The following Engineering personnel have engaged in various activities in conjunction with the project during the report period.

PROJECT DIRECTOR

Dr. Darrell E. Newell, Ph.D.

EDUCATION: BSEE, Iowa State University, 1952
MSEE, State University of Iowa, 1956
Ph. D. in EE, State University of Iowa, 1958

EXPERIENCE: From June 1961 to present - Dr. Newell is the Senior Engineer in charge of research, design and development of products within the Electronics Engineering Section. Representative projects include; development of new techniques in cryogenic liquid level measurement and flow measurement for missile and space applications, preliminary development of complete propellant management system for Saturn II vehicle, development of new techniques for temperature compensation of crystal oscillators, development of a new crystal type cryogenic thermometer and other internal sponsored development projects directed towards advance applications in space and missile technology.

From June 1959 to May 1961 - Associate Professor in the Research Section of the Electrical Engineering Department at the State University of Iowa. Some of the projects under his jurisdiction included:

1. Study of temperature compensation circuitry for quartz crystal oscillators.
2. Investigation of the short-term instability of regenerated dividers.
3. Investigation of mechanical refrigerator suitable for cooling quartz crystals.
4. Investigation of parametric amplification, oscillation, multiplication and conversion.
5. Nuclear Gyroscope Projects.

From 1952 to 1959 - Dr. Newell was employed by Collins Radio Company, Cedar Rapids, Iowa. During this period when academic endeavors were pressing he was employed as a consultant and the remaining time as a Research Engineer in charge of such projects as propagation, excitation and function generator control problems.

1949 to 1952 - Transmission Engineer for WOI-AM-FM-TV

PROFESSIONAL AFFILIATIONS:

1. Member and Officer of Institute of Radio Engineers
2. Registered Professional Engineer of Iowa
3. Member of Iowa Academy of Science
4. Maintains First Class Radio - Television Commercial License

PATENTS:

1. Switching Circuitry
2. Automatic Frequency Control
3. Frequency Stabilizing Networks

PUBLICATIONS:

1. "Research Modulation" published by Collins Radio Company.
2. "An Investigation of Noise and Function Generators" published by Collins Radio Company.

PROJECT ENGINEER

Richard H. Bangert

EDUCATION: AA, Keokuk Community College, 1958
BSEE, State University of Iowa, 1961
Graduate work towards MSEE, State University of Iowa

EXPERIENCE: August 1961 to present - Mr. Bangert is the Project Engineer in charge of the Frequency Synthesis and Control Group. Projects under his direct supervision include:

1. Phase-Locked Frequency Dividers
2. Temperature Compensated Oscillators
3. Miniature Oscillators
4. Frequency Standards
5. 50 Megacycle Phase-Locked Loop System
6. Ultra-Stable Telemetering Oscillators
7. Research Study for Signal Corps Temperature Compensated Quartz Crystal Oscillators

February 1960 to August 1961 - Mr. Bangert worked as a graduate assistant in the Electrical Engineering Department at the State University of Iowa. Projects included; temperature compensation of quartz crystal oscillators, circuitry design for temperature compensation of quartz crystal oscillators, designed computer program for IBM 7070 to find a means of synthesizing temperature compensation networks.

PROFESSIONAL AFFILIATIONS: Member of Institute of Radio Engineers

PATENTS: 3 pending, Temperature Compensation of Quartz Crystal Oscillators

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ATTN: SELRA/PF, Technical Staff (Record Copy)	1		
ATTN: SELRA/PFP, Miss M. Herberg	3	This contract is supervised by the Solid State and Frequency Control Division. Electronic Components Department, USAELRDL, Fort Monmouth, New Jersey. For further technical information, contact the Project Engineer, Mr. Stanley S. Schodowski, Telephone 535-2778 (New Jersey Area Code 201).	
ATTN: SELRA/PFP, S. Schodowski	16		
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Bell Telephone Laboratories, Inc. ATTN: Mr. Roger A. Sykes 555 Union Boulevard Allentown, Pennsylvania	1		

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FREQUENCY TEMPERATURE COMPENSATION TECHNIQUES
FOR QUARTZ CRYSTAL OSCILLATORS
by R. H. Bangert

First Quarterly Report, 1 July 1963 to 30 September 1963.
53 pages including figures. Contract No. DA 36-039 AMC-
02282(L). Unclassified report.

This report discusses the results of investigation into the characteristics of temperature compensated crystal oscillators. A new compensation circuit using a diode switch is discussed and results are given on a number of experiments. Crystal and compensation networks are discussed to show the reasons for some types of non-linearities that occur in the $\Delta f/f$ versus temperature characteristic of TCXO's. Voltage regulation and voltage regulator requirements are shown and results of one voltage regulator circuit are given. The effect of adjusting frequency is shown and possible methods of obtaining negligible effect on the compensation characteristics are examined. The initial design of a miniature TCXO is presented.

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1. TCXO Design
2. Diode Switch
3. Frequency Adjustment
4. Crystal Characteristics
5. Voltage Regulation
6. Conclusions

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5. Voltage Regulation
6. Conclusions

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THE BENDIX CORPORATION
PIONEER-CENTRAL DIVISION
Davenport, Iowa

FREQUENCY TEMPERATURE COMPENSATION TECHNIQUES
FOR QUARTZ CRYSTAL OSCILLATORS

by R. H. Bangert

First Quarterly Report, 1 July 1963 to 30 September 1963, 53 pages including figures. Contract No. DA 36-039 AMC-02282(E). Unclassified report.

This report discusses the results of investigation into the characteristics of temperature compensated crystal oscillators. A new compensation circuit using a diode switch is discussed and results are given on a number of experiments. Crystal and compensation networks are discussed to show the reasons for some types of non-linearities that occur in the $\Delta f/f$ versus temperature characteristic of TCXO's. Voltage regulation and voltage regulator requirements are shown and results of one voltage regulator circuit are given. The effect of adjusting frequency is shown and possible methods of obtaining negligible effect on the compensation characteristics are examined. The initial design of a miniature TCXO is presented.

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