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AD

FREQUENCY TEMPERATURE COMPENSATION TECHNIQUE
FOR
QUARTZ CRYSTAL OSCILLATORS

SEMI-ANNUAL REPORT

BY

DR. D. E. NEWELL
HOWARD D. HINNAH

REPORT NO. 1

JUNE 1968

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

CTS Knights, Inc.
Sandwich, Illinois

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Technical Report ECOM-0433-1

FREQUENCY TEMPERATURE COMPENSATION TECHNIQUE

FOR

QUARTZ CRYSTAL OSCILLATORS

SEMI-ANNUAL REPORT
1 June 1967 to 1 December 1967
Report No. 1

Contract No. DAAB07-67-C-0433
DA Project No. 1H6-22001-A-058, Task 02

Prepared By
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Howard D. Hinnah

CTS Knights, Inc.
Sandwich, Illinois

For
United States Army Electronics Command, Fort Monmouth, N. J.

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ABSTRACT

This report discusses the results of the investigation for the first six months of the contract. A new concept in compensation circuitry has been borrowed from analog computor nonlinear function generator theory and is being utilized in an effort to make the compensation process automatic.

Automatic compensation equipment has been investigated and a complete automatic compensator is currently being constructed.

Thermal transient characteristics have been analyzed, and some empirical data taken.

Several oscillator circuits have been analyzed.

Crystal specifications for 2×10^{-7} and 5×10^{-8} type resonators have been developed.

The following sections present the development of the above tasks.

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GENERAL

The purpose of this project is to advance frequency temperature compensation techniques for miniature quartz crystal oscillators having frequency temperature stabilities of $+2 \times 10^{-7}$ (Group I) and $+5 \times 10^{-8}$ (Group II) over the specified operating ambient temperature ranges. The objective of the project is to simplify frequency temperature compensation networks and the associated compensation procedures in order to realize a significant unit cost reduction.

An investigation of the cost distribution encountered in the generation of TCXO's indicate the largest contributor to manufacturing expense is compensation time. Consequently, this would be the most fruitful place to investigate, for the reduction of cost. An ideal solution to this problem would be the ability to utilize automatic compensation equipment. This would permit groups of TCXO's to be compensated automatically.

As this vehicle is considered for high performance TCXO's it becomes immediately apparent that the method of forming networks must be modified. Perhaps, the method that has the greatest flexibility will be the type commonly called "piece-wise linear compensation". This approach means that the entire temperature range is designed into segments and networks are generated to approach the curve in a linear or expediential manner in a given segment. As the temperature goes to a new segment, a new network would be in effect. From this it can be seen that an automatic device would only be required to adjust the network in the specific temperature increment and perhaps this function could be performed automatically.

The generation of this orthogonal incremental network and the equipment to adjust it automatically are the primary objectives of this research contract. If such a device could be generated, it is easy to see the effect it would have on the cost of the TCXO's.

-1-

CRYSTAL SPECIFICATIONS

The TCXO crystal investigation has resulted in preliminary specifications for six crystals. There are two crystals each for Group I-A, I-B and II. The two different types for each group are a Coldweld and a glass enclosure.

In writing the specifications for these crystals, two equally important requirements were adhered to as closely as possible. The first requirement was that the crystal specifications would result in a unit with tight enough parameter tolerances, such that it would lend itself to automated compensation. The second requirement was that the crystal specifications would result in a unit with loose enough parameter tolerances such that the unit would be a relatively low priced crystal.

With this objective to work to, the following preliminary specifications were written. Crystals have been constructed to these specifications. The outcome of the remaining work to be done on this contract will determine whether these specifications need to be changed.

The specifications for these crystals are shown in Appendix A.

THERMAL ANALYSIS

To insure that a TCXO will stay within the frequency tolerance specified over temperature, the design engineer must be concerned with the rate at which the ambient temperature can change. To demonstrate this characteristic, an anaylsis of a simple TCXO can be used.
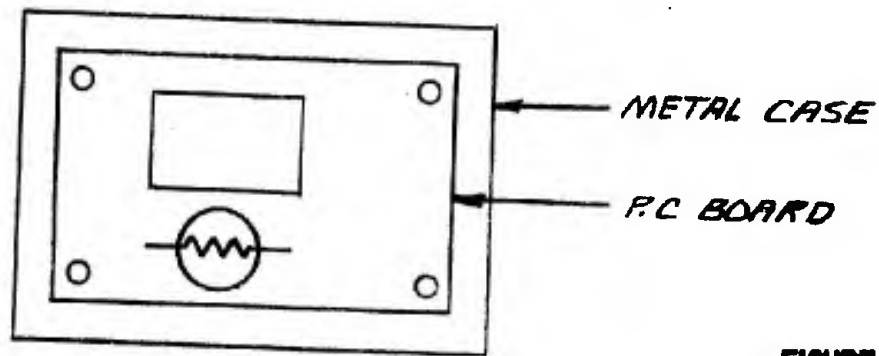
FIGURE 1

In the figure shown above, we have the simplest of TCXO's; one temperature sensor and the crystal. Assumed temperature effects on all other components are insignificant. (While this is not valid, it must be remembered, we are striving to demonstrate a general characteristic.) Assume that the resonator and sensor are point thermal sinks. With these assumptions, the equivalent circuit will then reduce to the simple one shown in the figure below.

FIGURE 2

-3-
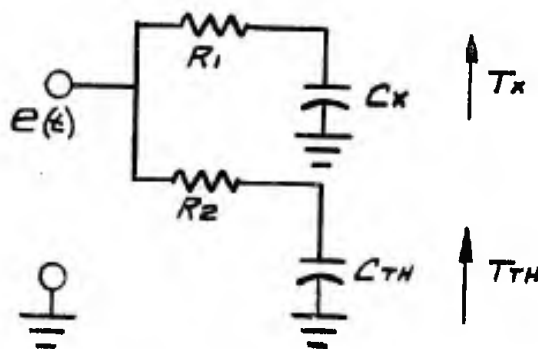
Thermal Analysis, Continued.

Where R_1 is thermal conductivity of the PC board to crystal, and R_2 is the thermal conductivity of the PC board to the thermistor. Assume the case has the same temperature at all points.

Then:

$$e(t) = R_1\frac{dg}{dt} + \frac{q}{C_x}$$

$$e(t) = R_2\frac{dg}{dt} + \frac{q}{C_t}$$

Then: $T_x = \dfrac{q_1}{C_x}$ (Temperature of crystal)

and $T_{th} = \dfrac{q_2}{C_{th}}$ (Temperature of thermistor)

Of course it is desired to keep $T_x = T_{th}$ regardless of the function represented by $e(t)$.

Case I. Assume $e(t) = E$ or a step function change in temperature.

$$E = R\frac{dg}{dt} + \frac{q}{C}$$

$$\frac{E}{S} = R_s\, q(s) - R_q(o) + \frac{q(s)}{C}$$

$$\frac{E}{S} + R_q(o) = \left\{Rs + \frac{1}{C}\right\}q(s)$$

$$q(s) = \frac{E}{S\left(Rs + \dfrac{1}{C}\right)} + \frac{R_q(o)}{Rs + \dfrac{1}{C}}$$

$$= \frac{E/R}{S\left(S + \dfrac{1}{RC}\right)} + \frac{q(o)}{S + \dfrac{1}{RC}}$$

$$q(t) = EC\left\{1 - e^{-t/RC}\right\} + q(o)\, e^{-t/RC}$$

$$= EC - EC_e^{-t/RC} + q(o)\, e^{-t/RC}$$

$$= EC + (q(o) - EC)\, e^{-t/RC}$$

Since: $T = q(t) = E + \left(\dfrac{q(o)}{C} - E\right)e^{-t/RC}$

-4-

Thermal Analysis, Continued.

Assume $q(o) = o$
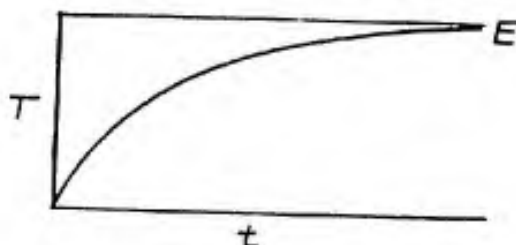
$$T = E(1 - e^{-t/RC})$$

Hence, the relationship between T_x and T_T

$$Tx = E(1-e^{-t/R_1 C_x})$$

$$T_T = E(1-e^{-t/R_2 C_T})$$

$$\triangle T = T_T - T_x = E(1-e^{-t/R_2 C_T})$$
$$- E(1-e^{-t/R_1 C_x})$$

$$= E(1-e^{-t/R_2 C_T} - 1 + e^{-t/R_1 C_x})$$

$$= E(e^{-t/R_2 C_T} - e^{-t/R_1 C_x})$$

$$E \left\{ e^{-t/R_2 C_T} - e^{-t/R_1 C_x} \right\}$$

Let $\alpha = \dfrac{1}{R_2 C_T}$ + $B = \dfrac{1}{R_1 C_x}$

in general $\alpha > B$

$$E \left\{ e^{-t\alpha} - e^{-tB} \right\}$$

$$E e^{-t\alpha} \left\{ 1 - \dfrac{e^{-tB}}{e^{-t\alpha}} \right\}$$

$$E e^{-t\alpha} \left\{ 1 - e^{-t(B-\alpha)} \right\}$$

$$E e^{-t\alpha} \left\{ 1 - e^{+t(\alpha-B)} \right\}$$

It can be seen that the $-B$ term is a figure of merit term. As an example if $\alpha - B = o$ $\triangle T = 0$

Figure 3 is a picture of a heat sink of the type discussed.

FIGURE 3
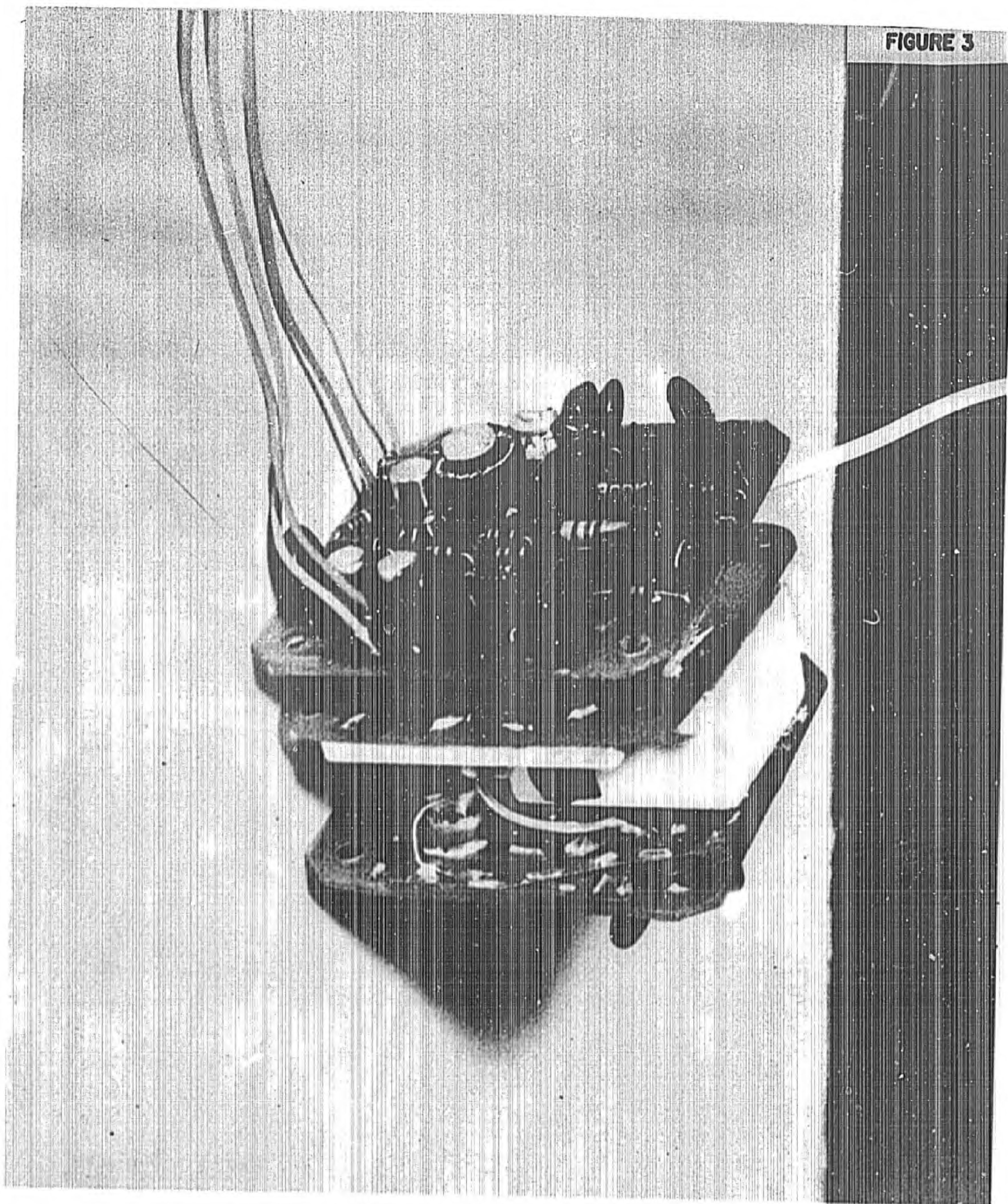
THERMALLY INTEGRATED TCXO

SEGMENTED COMPENSATION NETWORKS

Considerable effort has been expended on the segmented temperature compensation network investigation. More effort is necessary and is being applied to this portion of the the contract in order to perfect this technique to the degree necessary for an automated application.

An example of the progress being made on this portion of the contract can be seen in Figures

Figure 4 shows a segmented network which has been designed for a 5 MC TCXO. The dotted line shows the final composite voltage versus temperature characteristics of the segmented network. The solid lines represent a $\pm$ 1 PPM error band. Calculations have shown that this network should compensate the unit to $\pm$ 3.5 x 10^{-7}. Figure 4 shows which segment of the network is in effect for a given temperature range. To improve the stability over temperature, additional segments will be needed. At this point in the project, it appears that 7 or 8 segments will be necessary to meet the final stability objectives of the Group I-A and I-B oscillators. When the network of Figure 4 is operated on by the automatic compensator resistor values R_1, R_2, R_3, and R_4 would be selected automatically.

The total range voltage versus temperature characteristics of each segment are shown in Figures 5, 6, 7 and 8. By super-imposing these four curves, it demonstrates more clearly where each segment is in effect.

Since active elements have been added in this type of network, it is necessary to look at the possible error contributions from transistors. The transistors are all utilized in an emitter-follower type of circuit. The equations that will determine the error contributions of the semi-conductor devices in this type of circuit are shown in Figures 9 and 10. These are only preliminary calculations and additional work will be done to determine the significance, if any, of the actual error contributions.

FIGURE 4

SEGMENTED COMPENSATION NETWORK
COMPOSITE VOLTAGE VS TEMPERATURE

-8-

FIGURE 5

SECTION A
VOLTAGE VS TEMPERATURE

VOLTS

°C

-6-

FIGURE 6

SECTION 8
VOLTAGE VS TEMPERATURE

VOLTS

-10-

FIGURE 7

SECTION C
VOLTAGE VS TEMPERATURE

VOLTS

°C

-11-
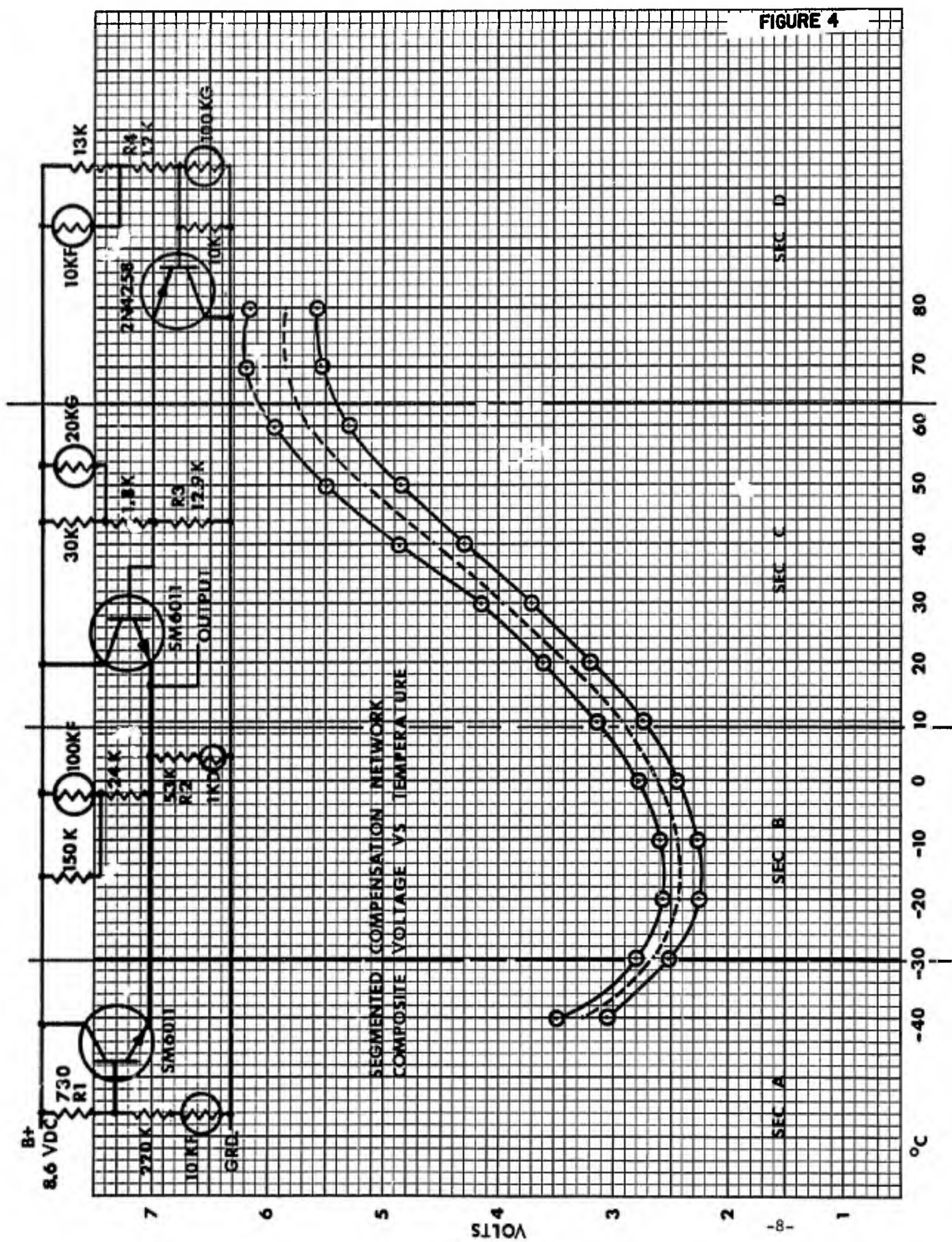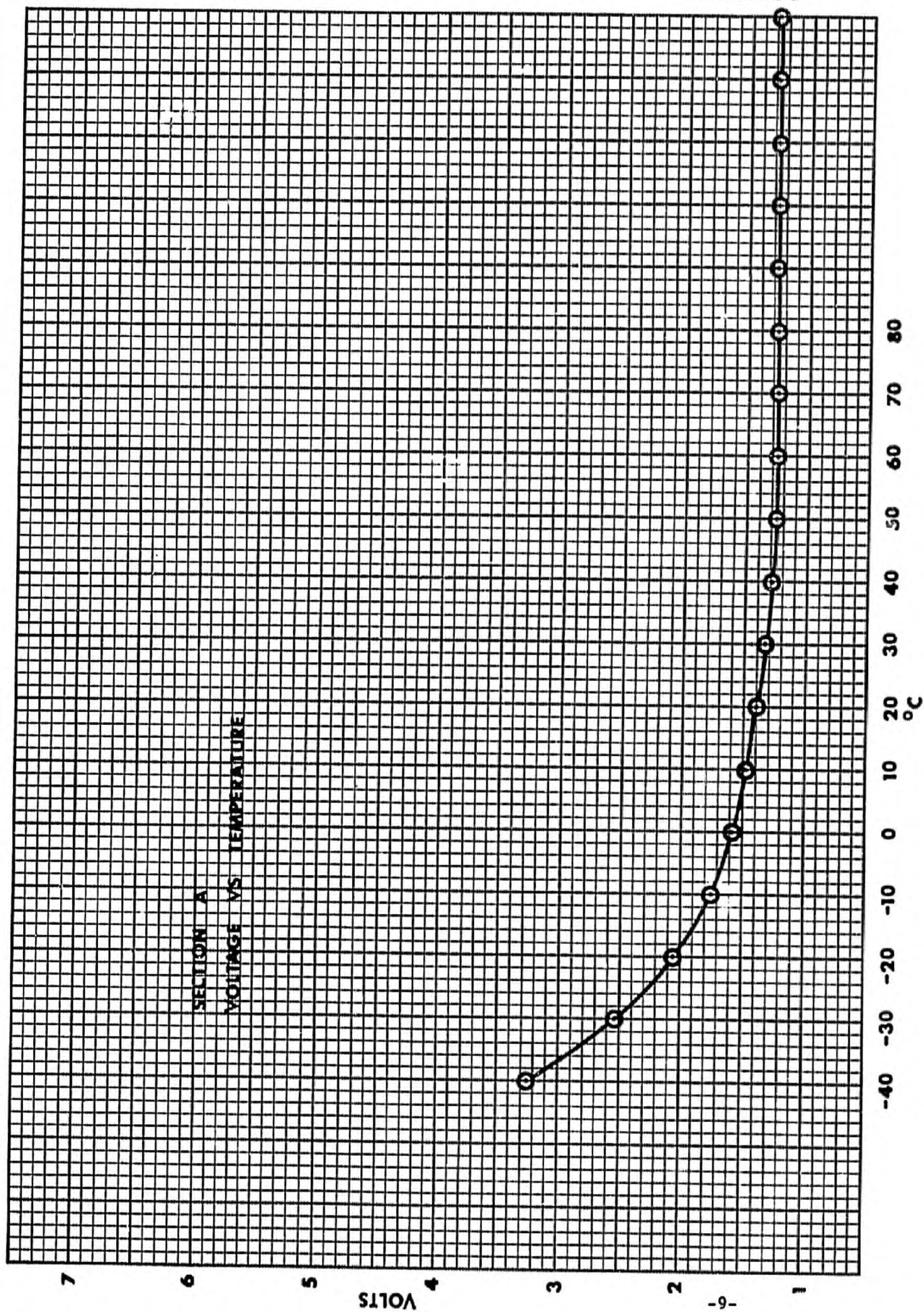
FIGURE 8

SECTION D
VOLTAGE VS TEMPERATURE

VOLTS

-40 -30 -20 -10 0 10 20 30 40 50 60 70 80
°C

-12-
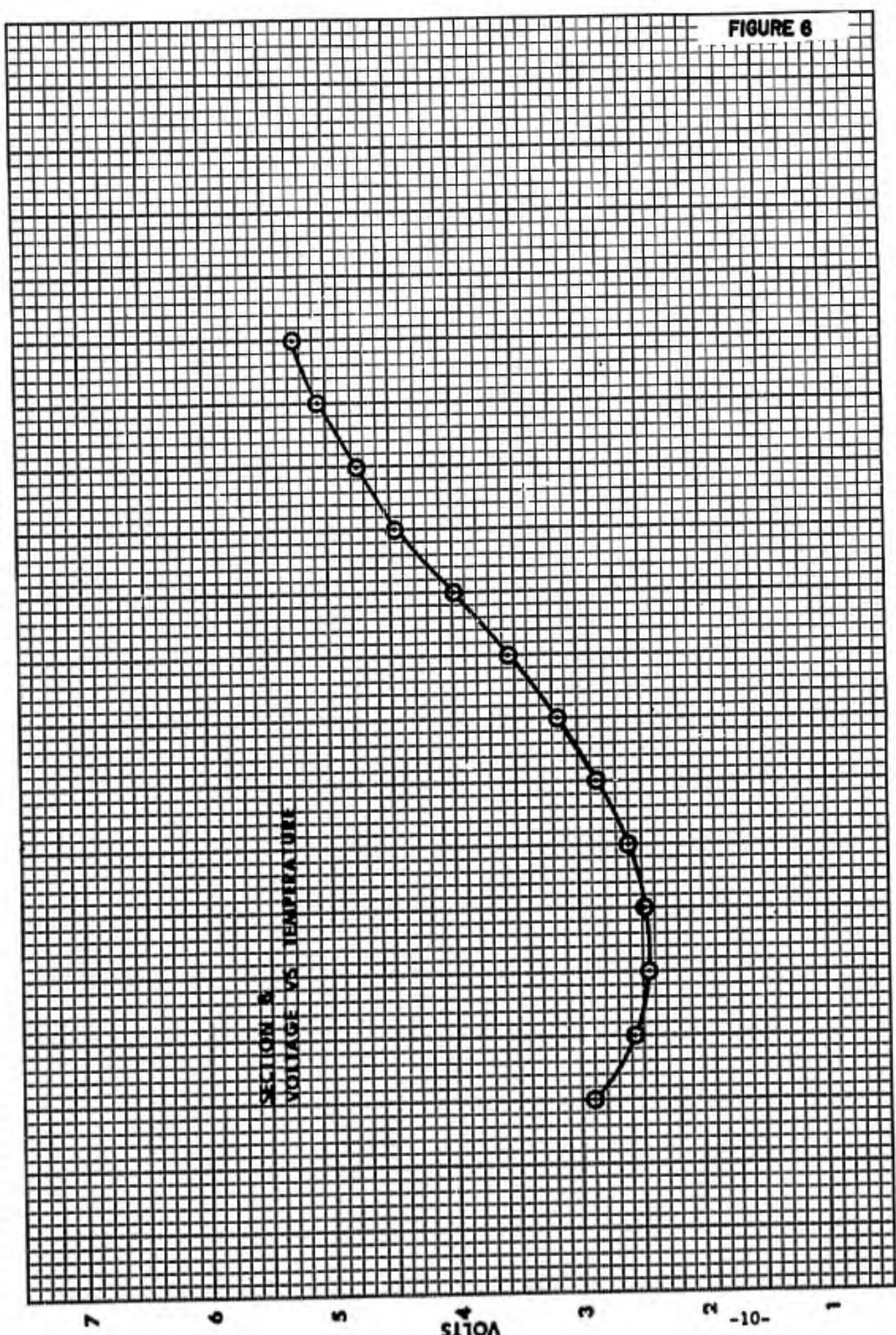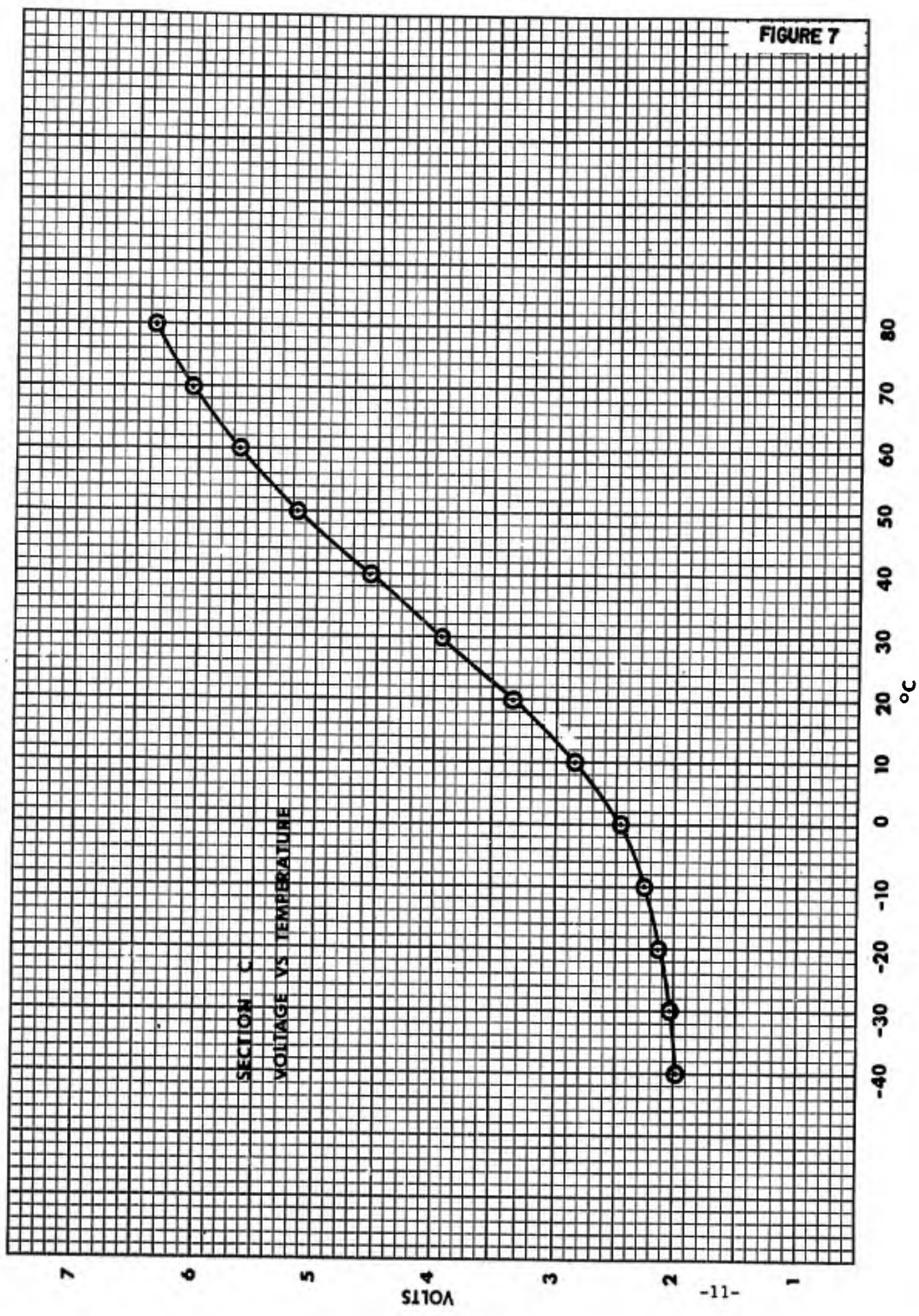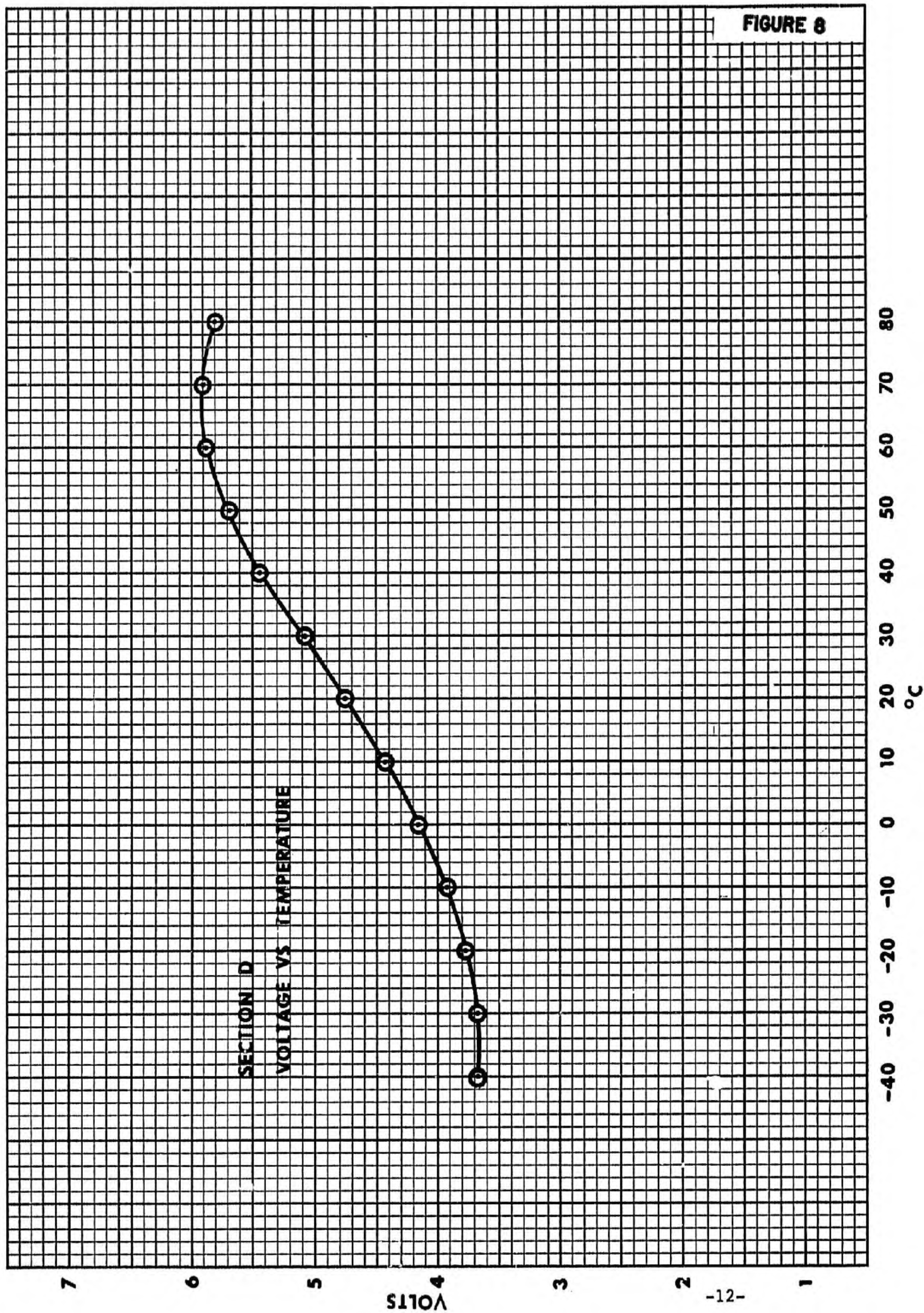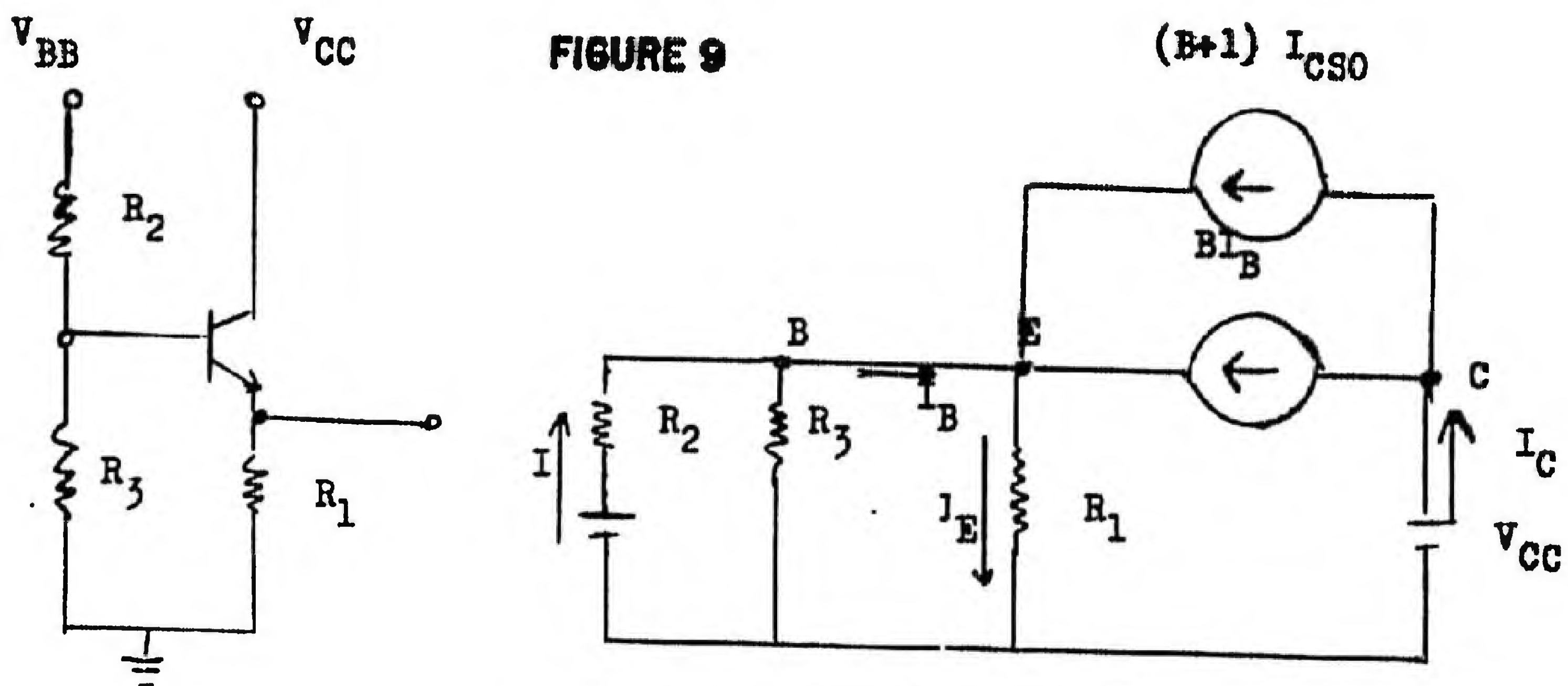
FIGURE 9

DC Equivalent

$$I_C = \frac{\alpha R_3 V_{BB} + I_{CBO}\left[R_1(R_2 + R_3) + R_2 R_3\right]}{R_1(R_2 + R_3) + (1-\alpha) R_2 R_3}$$

$$E_0 = \frac{\alpha R_1 R_3 V_{BB} + I_{CBO}\left[R_1^2(R_2 + R_3) + R_1 R_2 R_3\right]}{R_1(R_2 + R_3) + (1-\alpha) R_2 R_3}$$

Therefore $R_2 = R_4 + R_5$

FIGURE 10

$$V_{BB} + V_{EE}$$

$$E_0 = \frac{\alpha R_1 R_3 V_{EE} + I_{CBO}\left[R_1^2(R_0 \cdot e^{B(\frac{1}{T} - \frac{1}{T_0})} + R_4 + R_3) + R_1 R_3(R_4 + R_0 \cdot e^{B(\frac{1}{T} - \frac{1}{T_0})})\right]}{R_1(R_3 + R_4 + R_0 \cdot e^{B(\frac{1}{T} - \frac{1}{T_0})}) + (1-\alpha)(R_4 + R_0 \cdot e^{B(\frac{1}{T} - \frac{1}{T_0})}) R_3}$$
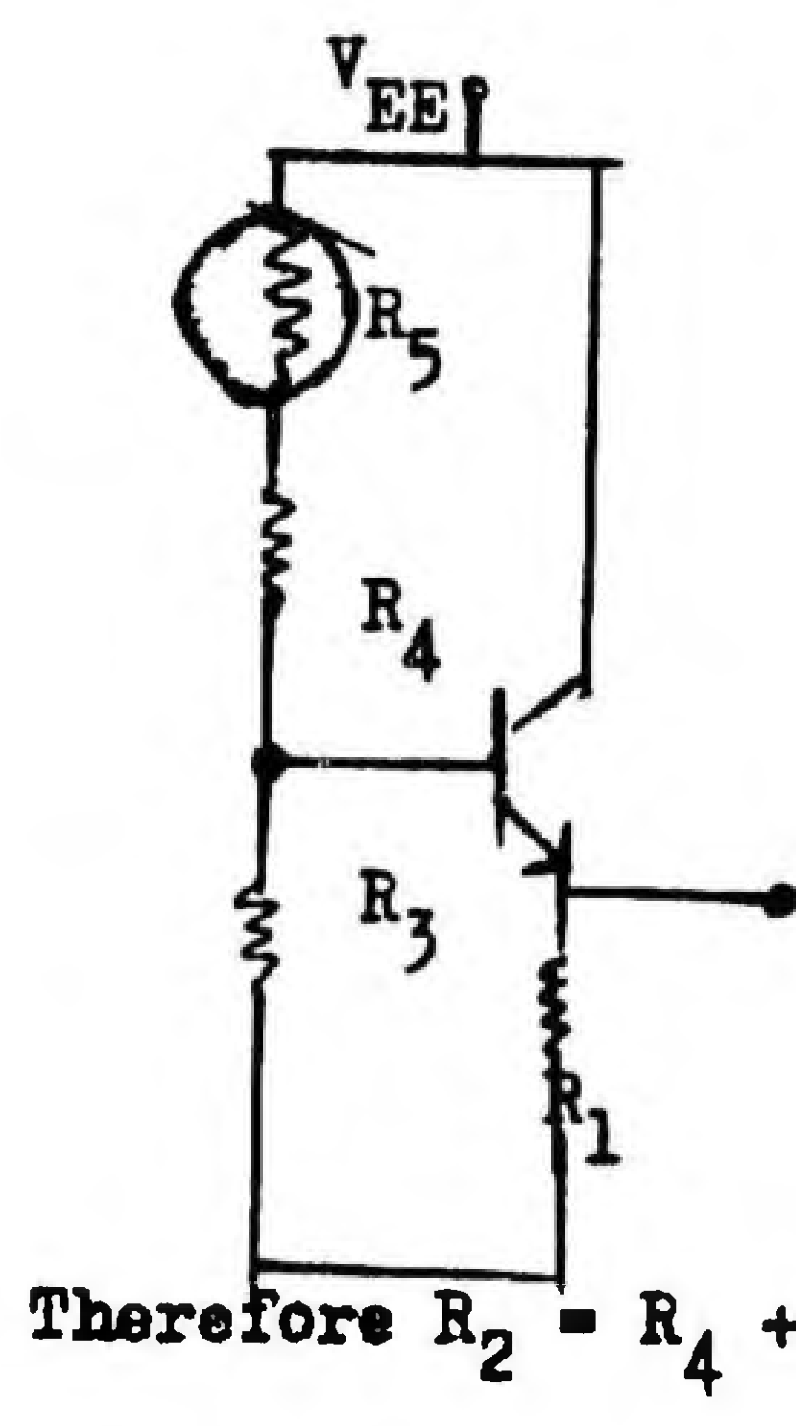
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AUTOMATIC TEST EQUIPMENT

At the initiation of the project, three systems of automatic compensated equipment were considered. System One utilized a digital approach, System Two used an analog approach and System Three used both analog and digital devices with a computer for control and a core memory for storage. Each of these systems will be discussed in the following sections.

SYSTEM ONE. Digital Approach

Figure 11 is a block diagram of one of the digital systems considered. While the system utilized an analog system for generating temperature control, the main portions of the loop are composed of pulse activated deivces. While this system has the advantage of being able to dial in reference frequency, which would mean it could be operated easily with unskilled labor, the memory section of the unit is cumbersome and expensive. The varying resistance function would almost have to be generated by a latter network when one considers that each segment's resistance should remain in the circuit while the other segments are being determined that as many as 7 to 10 latter networks could be required by a single oscillator.

In addition, the shift register would lose it's memory if power was lost. Consequently, an entire run's information could be lost if a power failure occured near the end of the run. Hence, it was decided that the digital approach to the equipment left something to be desired.

SYSTEM THREE. Computer Controlled System

System Three utilizing a similar digital computer has many advantages. Not only would the equipment compensate the TCXO's, it could run a variety of the tests on the oscillators at the same time. Several approaches to this equipment were investigated with the aid of the computer manufacturer. In each case, the equipment cost to generate such a system exceeded $60,000.00 and it was determined that at least at this time, a more economical approach would have to be found. It is believed that ultimately a system of this type can be used, not only to compensate the oscillators, but perform all required acceptance tests and provide both the manufacturer and the customer with a set of certified test data for each unit.

SYSTEM TWO. Analog Compensation Equipment

Figure 12 is a block diagram of the analog compensation equipment. While this particular system leaves something to be desired from the aspects of instrumentation, it can be utilized to demonstrate the practicability of the automatic compensation method and be generated for a relatively inexpensive expenditure.

Figure 13 is a picture of the automatic equipment constructed to date. This analog system has the advantages of retaining memory during power failures, since some of the resistors in the compensation network are motor driven potentiometers.

Figure 14 is a picture of the basic servo and Figures 15 and 16 are a plot of resistance versus time as the loop is perturbated first to the high side and then to the low side.
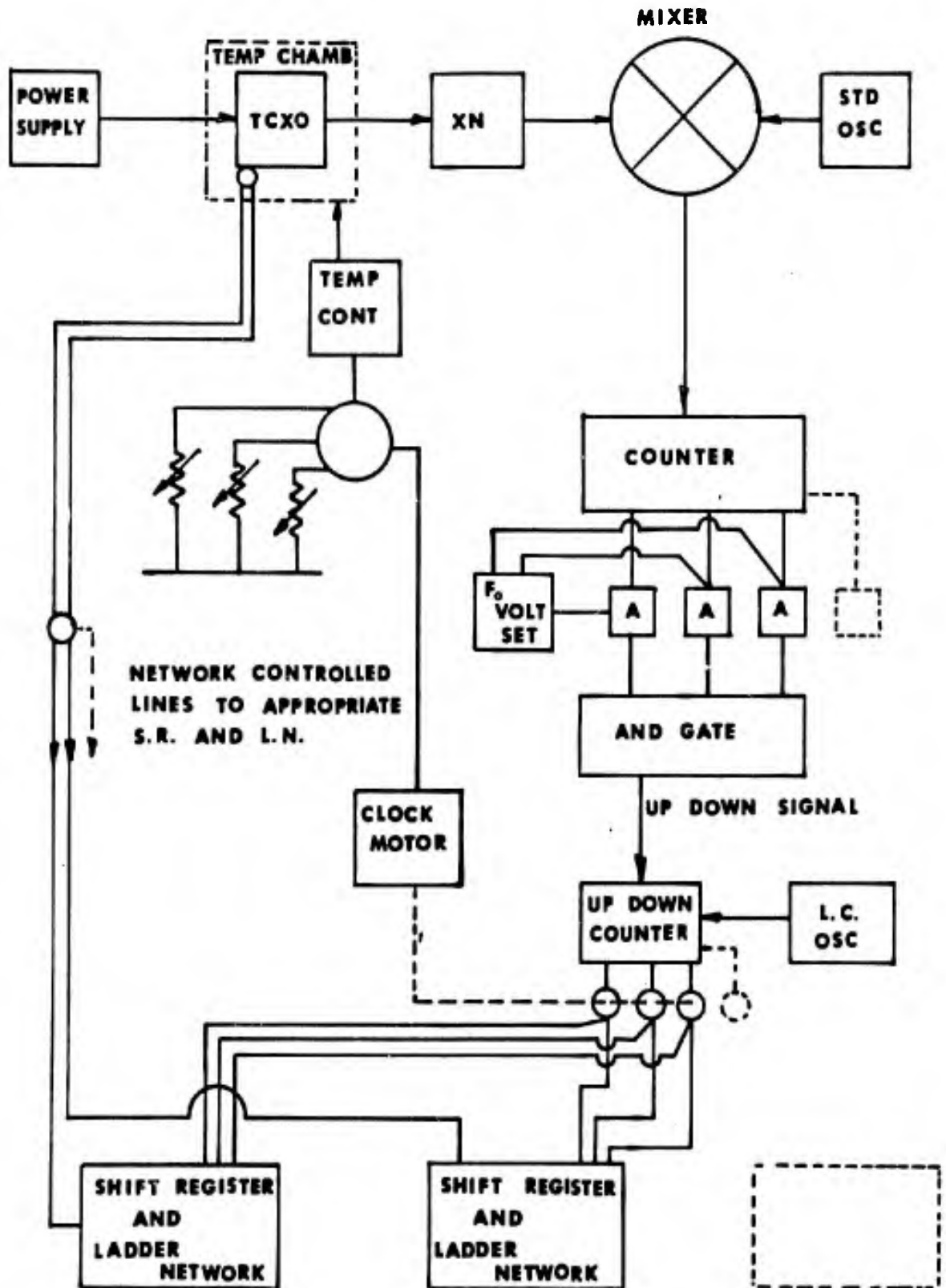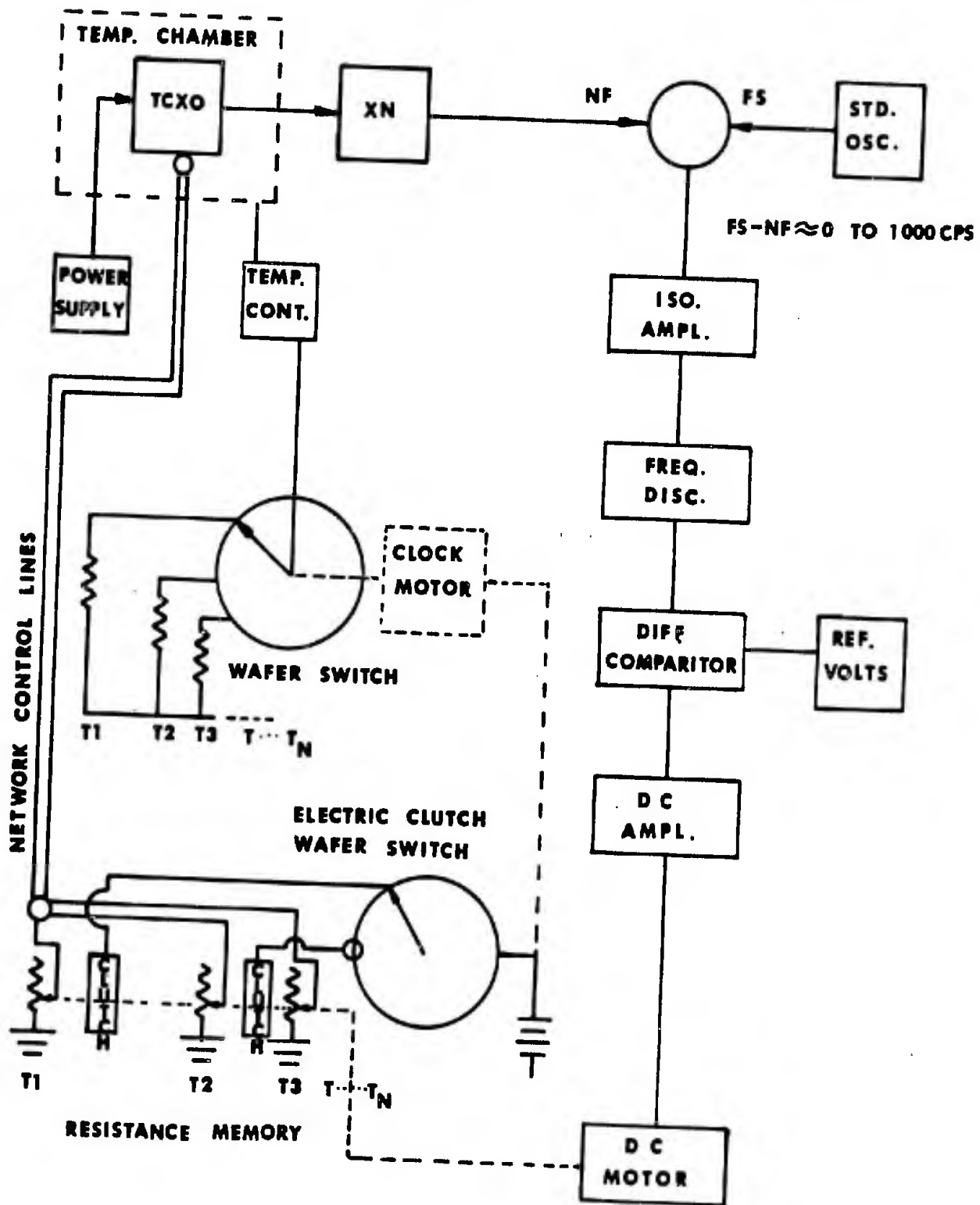
FIGURE 13
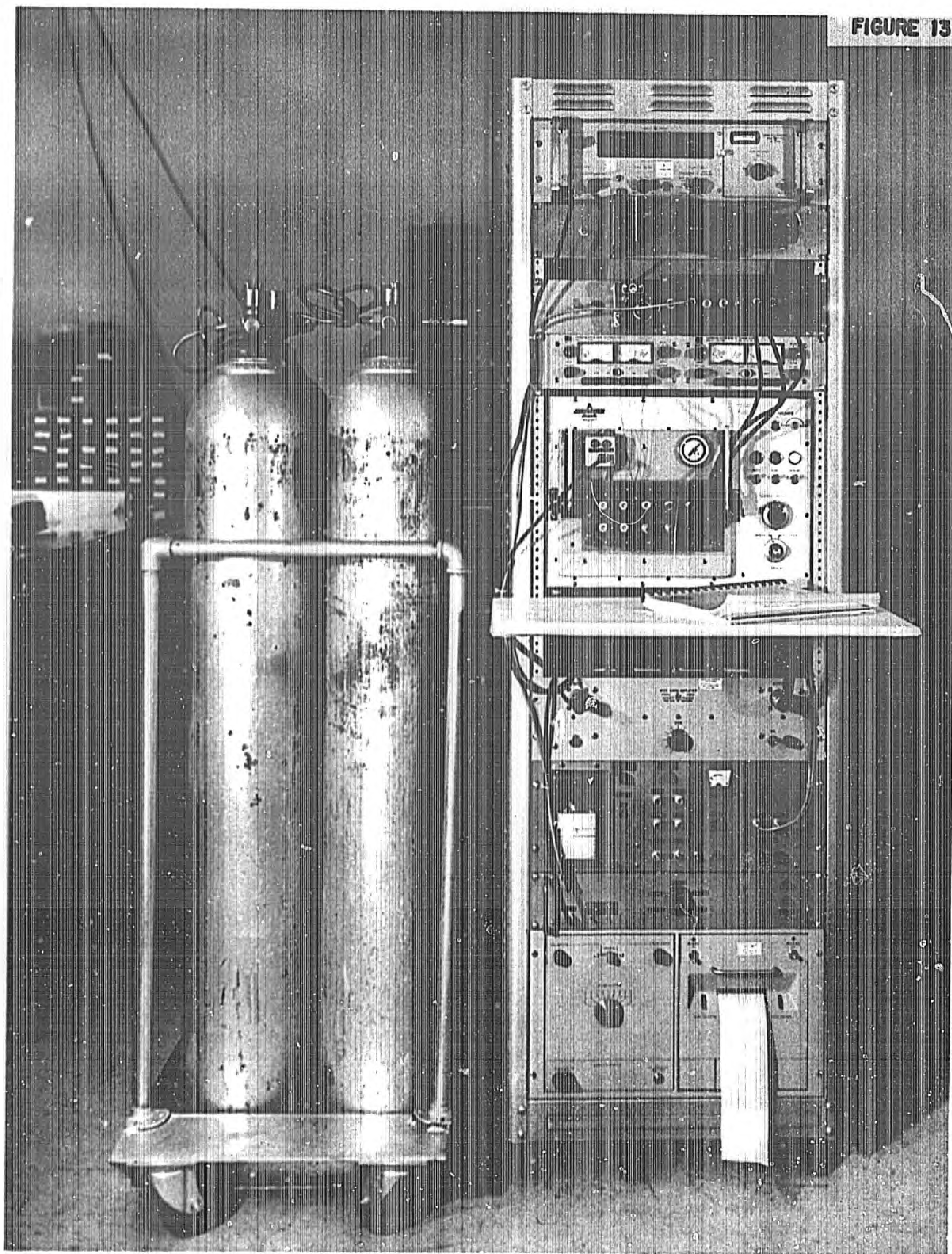
FIRST MODEL AUTOMATIC COMPENSATION EQUIPMENT

FIGURE 14
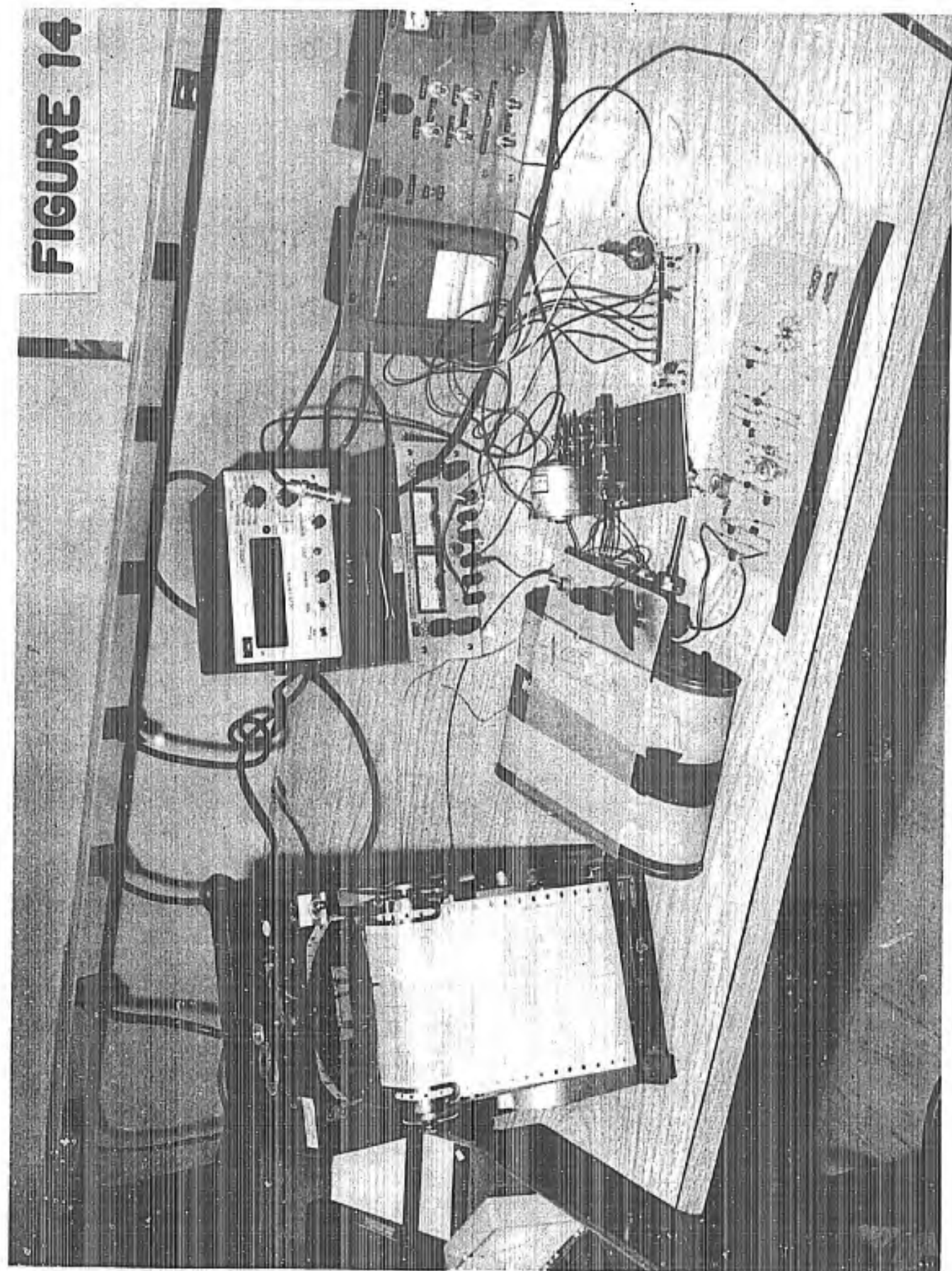
BREAD BOARD OF PHASE SERVO

FIGURE 15
SERVO RESPONSE

FIGURE 16
SERVO RESPONSE
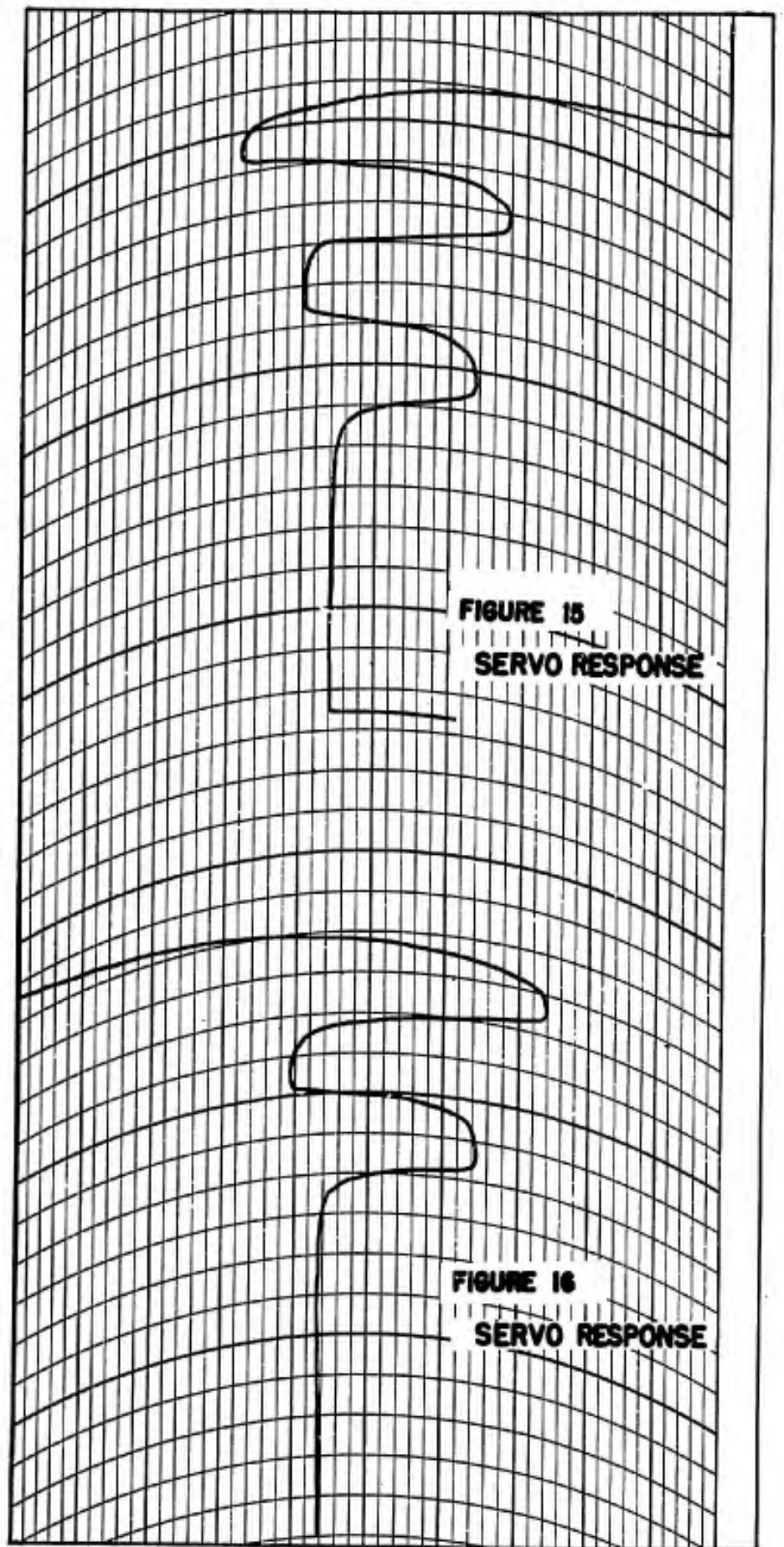
INTEGRATED TCXO CIRCUITRY

Currently, CTS Research Division is assembling the hybrid circuitry shown in Figure 17.

The resistors are thick film types deposited on an alumina substrat. In the layout for the substrat, areas have been left to add chip capacitors and varactors after this circuitry has been proven.

It is anticipated that all components, except certain network elements, trimmers and crystal can be placed on the substrat.

Figure 18   is a drawing of the circuit housing.
            (See Figures 18A and 18B)
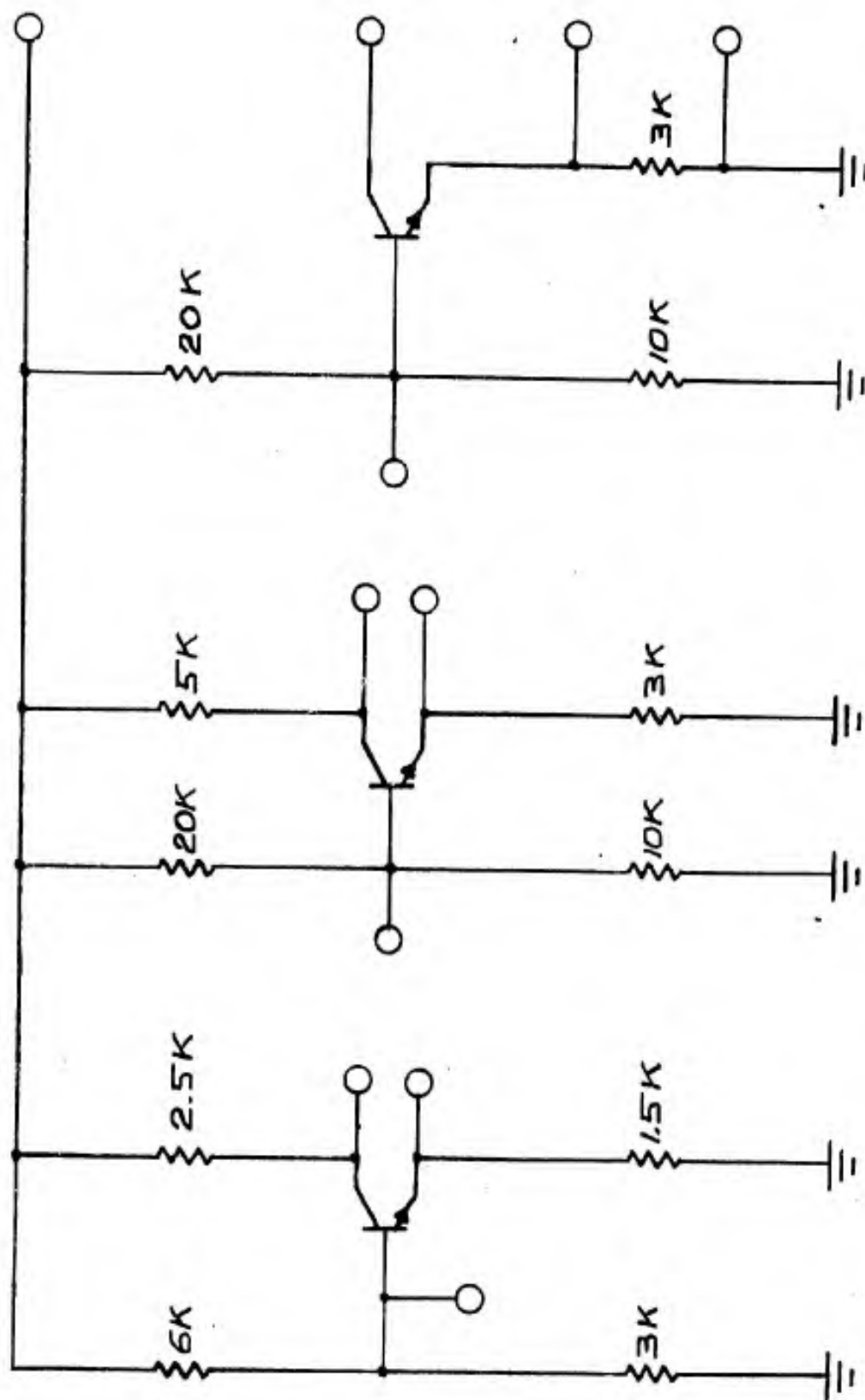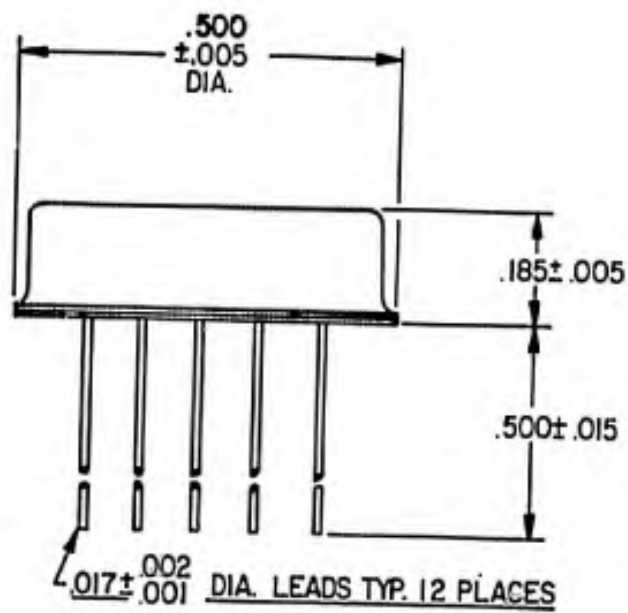
FIGURE 17
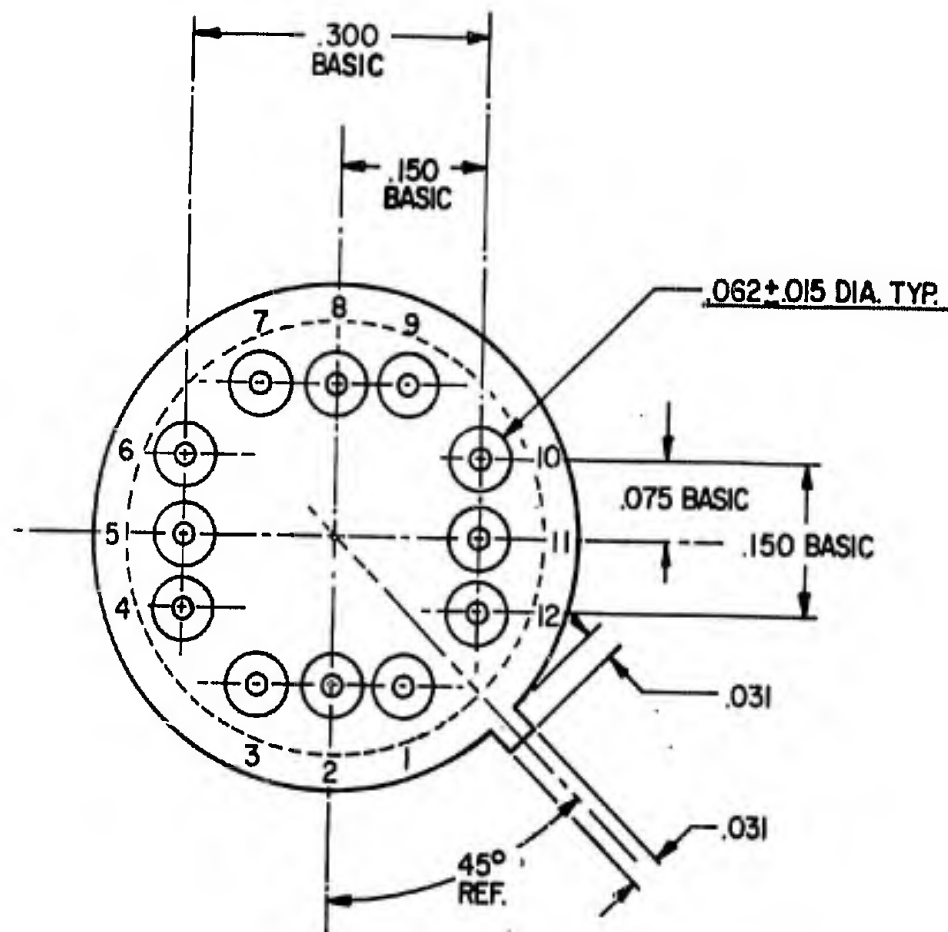
FIGURE 18A

FIGURE 18B

ANALYSIS OF OSCILLATOR CIRCUITRY

The following sections (See Appendix A) derive the load impedance that the crystal sees from various types of oscillators. While a complete oscillator analysis has not been completed, additional work is being performed to include active element apparent reactances. It is felt that by including all terms in the deviation, a more complete understanding of performance can be acquired.

MULTIPLE MODULATOR STUDY

Some effort has been expended in the utilization of multiple modulators to make the compensation task easier.

Figure 19 indicates a single stage modulator which is currently used in most TCXOs.

This type is quite adequate for TCXOs with stabilities of $\pm$ 1 PPM, and while they can be used to generate 5.10^{-7} units, the network required is difficult.

Many units utilizing the dual modulator shown in Figure 20 have been built and 5.10^{-7} units are readily obtainable. It is easily seen that utilizing multiple modulators has several advantages.

Assume, due to self rectification effects, coupled with supply voltage limitations, that the dynamic range allotted to a modulator is 2 to 6 volts. If a $\pm$ 25 PPM oscillator is being compensated to $\pm$ 5.10^{-7}, this means an improvement factor of 50, and the voltage error allowed is 4/50 or 80 mv. If a two modulator system is used, with the first modulator improving the stability by a factor of 10, the first network error could be 0.4 volt, and the second modulator could have an error of 0.8 volt, hence the network error band is considerably improved. This system can be used by putting a fixed coarse network in the oscillators and correcting for errors in modulator one with modulator two. Figure 21 is just an extension of the above discussion and is utilized to generate 1.10^{-7} units.

Some mention sould be made of what actually happens when multiple modulators are used. If a unit is built using three modulators with each network generated with the objective of being as close to zero error as possible, it will be discovered that the fine modulator will produce a voltage function that is very difficult to generate. This is easily seen, as one considers, that the error generated by the coarse network must be corrected by the inter-coarse network. In general, a second order first network curves error will generate a fourth order second network curve and the fine curve in turn, will become an eight order curve. These high order curves are difficult to fit, and in some cases negates the use of the additional modulator.

To minimize this effect some concern must be given this aspect, when the coarse and inter-coarse networks are generated and perhaps, an intentional error introduced at these networks will make the entire compensation task easier.

FIGURE 19

C_{V1}
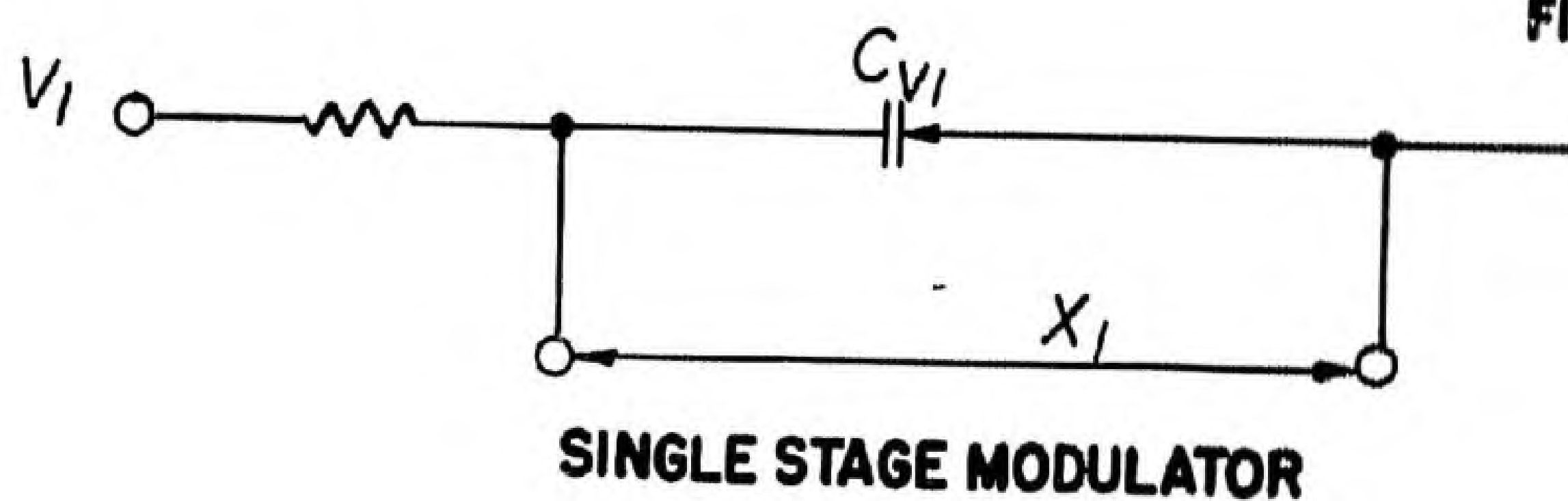
V_1

X_1

SINGLE STAGE MODULATOR

FIGURE 20

V_1

C_{V1}

C_1 C_{V2}

V_2

X_2

DUAL STAGE MODULATOR

FIGURE 21

C_{V1}

V_1

C_1 C_{V2}

V_2

C_2 C_{V3}

V_3

X_3

TRIPLE STAGE MODULATOR
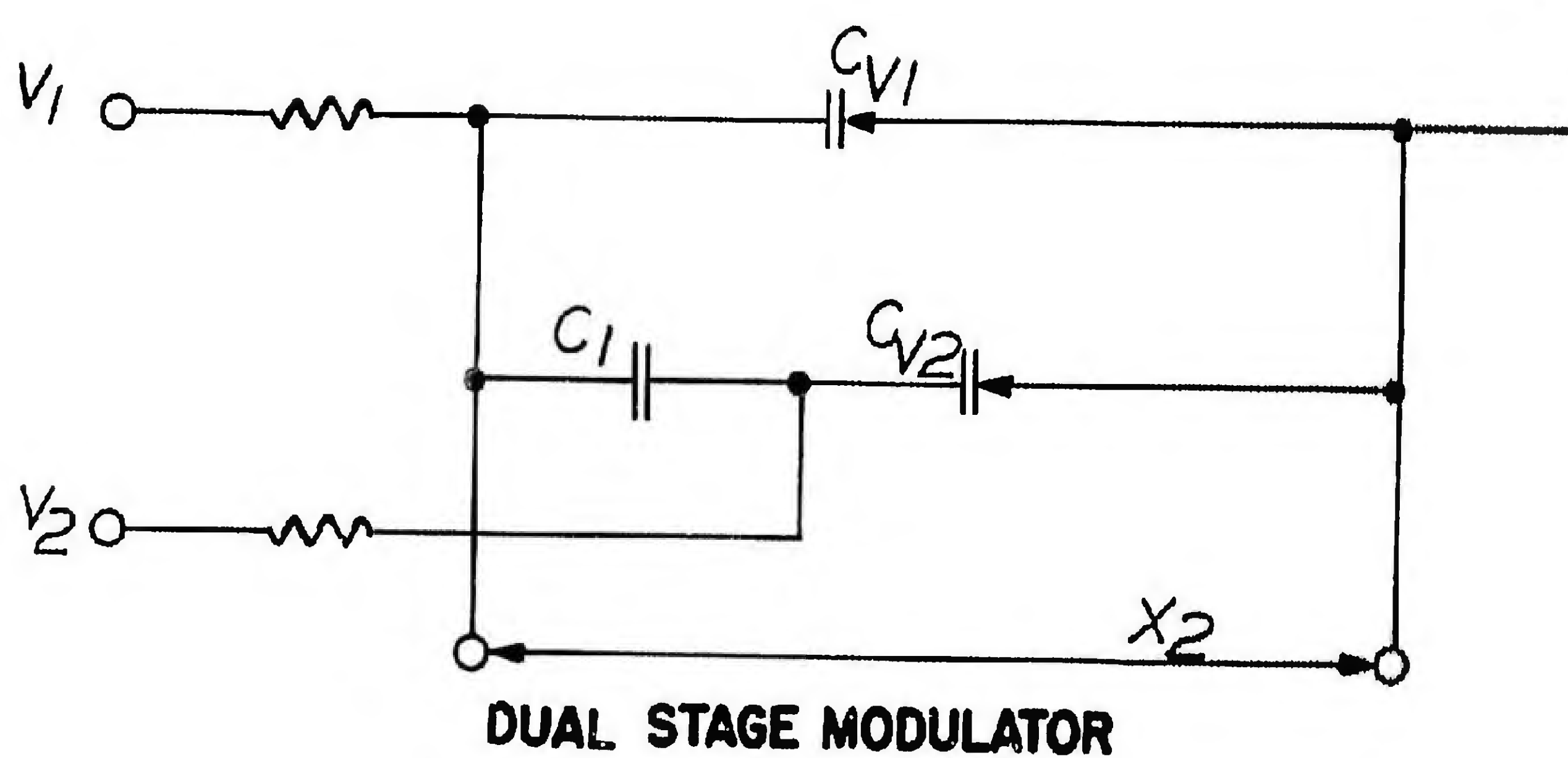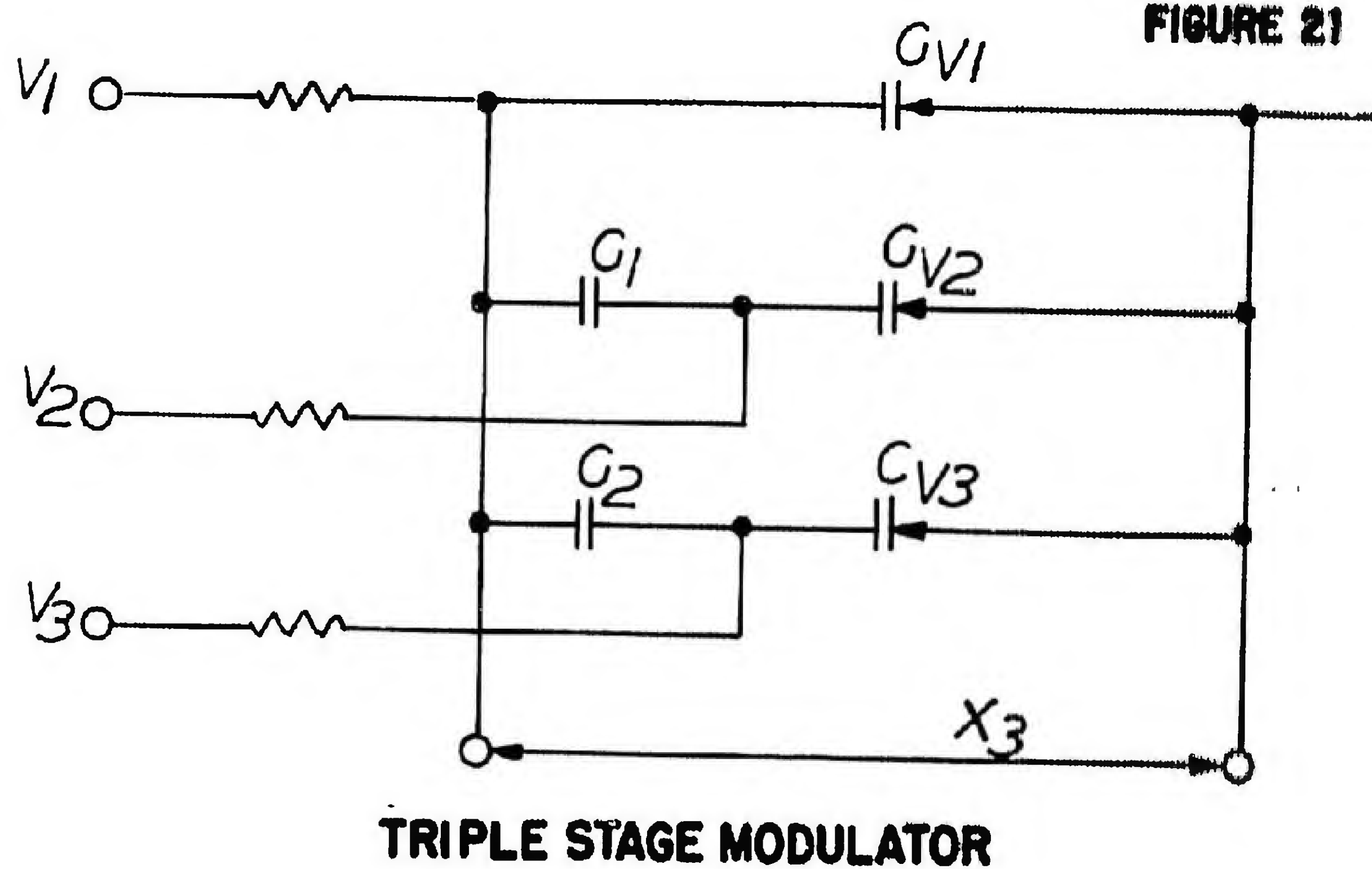
CONCLUSION

The project has not progressed as fast as scheduled during its first six months, however, several significant milestones have been passed. The selection of the type of automatic compensation equipment to use took considerably more time than was originally anticipated.

While the flexibility and multiple function characteristics of a computer system seem so desirable, it is believed that by first designing and using the analog system, that a better computerized system can be built at a later time. It was with reluctance however, that the computerized system was rejected at this time.

A piece-wise or segmented network has been utilized on TCXOs and the analog servo loop has been used to select a network resistance, hence it can be said that the milestone of feasibility has been passed. It merely remains to enlarge these functions and place switching control circuitry in the system to have a complete functioning compensation.

Considerable information concerning thermal transient behavior for TCXOs has been acquired, and an attempt has been made to theorectically predict this type of performance.

Some insight into the utilization of multiple modulators has been obtained, with specific emphasis on their utilization with automatic compensation equipment.

While at present, the project is behind schedule, with the allotment of more time from currently assigned personnel and the addition of more personnel, the project will be on schedule at the next six months review period.

APPENDIX A

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TCXO CRYSTAL SPECIFICATIONS

Group I-A (HC-27/U)

1. Operating Characteristics

   Frequency: 5 MC
   Cut and Mode: AT Fundamental
   Holder: HC-27/U
   Load Capacity: 32 pf
   Drive Level: 200 microamps
   Calibration Tolerance and Temperature:
   $\pm$ 3 PPM at 30°C
   Operating Tolerance and Range: -40 to +80°C
   LTP-UTP: 20 PPM + 5 PPM
   Unwanted Modes: -15 db
   Drive Stability: 1×10^{-9}/db
   Stability, Long Term: 1×10^{-8}/week at 60°C

2. Parameters

   C_0: 1.8 pf max.
   C_0/C_m: 300 $\pm$ 10%
   Resistance: 300 ohms max.
   Q: 2×10^5 min.

3. Environmental

   Shock: 50G, 11 ms, 3 planes
   Vibration: 20G, 50 to 2000 cps, 3 planes

4. Processing Specifications

   Diameter: .530"
   Quartz: Natural
   Contour: 2 Diop Plano-convex
   Angle: AT 35° 11.5' to 35° 13'
   Electrical Diameter: 150

NOTES:

1. WALL THICKNESS .035-.045 DESIRED
   THROUGHOUT. ACCEPTABLE:

   ZONE A - .027-.043 AND IN AREA
   TOWARD CLOSED END.

   ZONE B - .020-.045 CENTER CLOSED END.
   ZONE C - .011-.035 CORNER RADIUS
   CLOSED END.

2. USE THIS BULB WITH BASE 281-1702-0 ONLY.
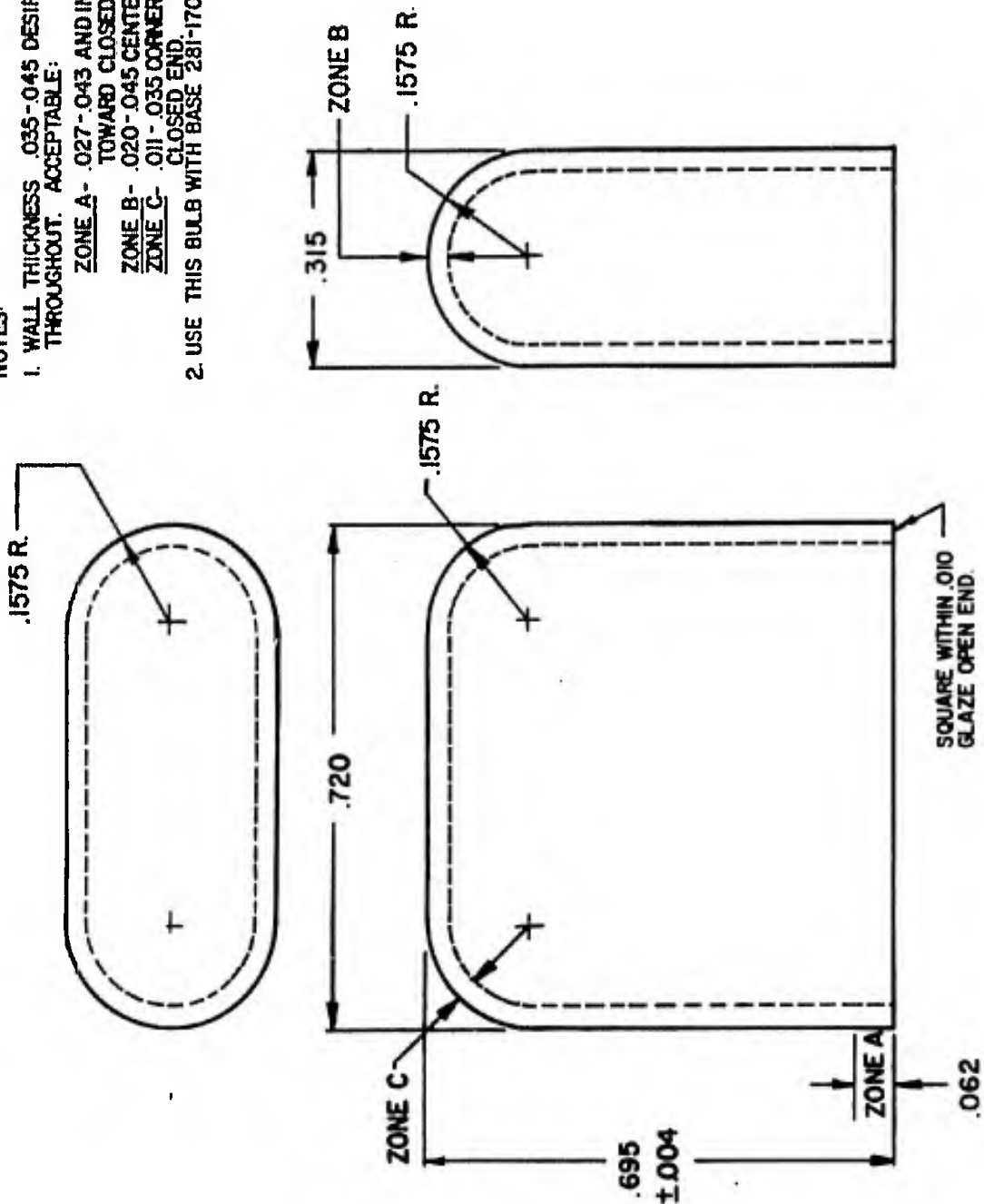
ZONE B

.1575 R.

.315

.1575 R.

.1575 R.

.720

ZONE C

.695 ±.004

ZONE A

.062

SQUARE WITHIN .010
GLAZE OPEN END.

FIGURE 22 A

-31-

.486

.321 ± .010

.215

.620

KOVAR RING
.293 x .700 (GLAZED)

.115

.095 ± .010

.450 MAX.

.238 ± .010/.015

7052 GLASS

KOVAR PIN

.052/.048

NOTES
1. USE THIS BASE WITH
   BULB 282-1702-0 ONLY.

.738/.718

FIGURE 22B

TCXO CRYSTAL SPECIFICATIONS

Group I-A (HC-6/U Type Coldweld)

1. Operating Characteristics

   Frequency: 5 MC
   Cut and Mode: AT Fundamental
   Holder: HC-6/U Coldweld
   Load Capacity: 32 pf
   Drive Level: 200 micro amps
   Calibration Tolerance and Temperature:
           $\pm$ 3 PPM at 30°C
   Operating Tolerance and Range: -40 to +80°C
   LTP-UTP: 20 PPM $\pm$ 5 PPM
   Unwanted Modes: -15 db
   Drive Stability: 1×10^{-9}/db
   Stability, Long Term: 1×10^{-8}/week at 60°C

2. Parameters

   C_o: 1.8 pf max.
   C_o/C_m: 300 $\pm$ 10%
   Resistance: 30 ohms max.
   Q: 2×10^5 min.

3. Environmental

   Shock: 50G, 11 ms, 3 planes
   Vibration: 20G, 50 to 2000 cps, 3 planes

4. Processing Specifications

   Diameter: .530"
   Quartz: Natural
   Contour: 2 Diop Plano-Convex
   Angle: AT 35° 11.5' to 35° 13'
   Electrical Diameter: 150

(.757 MAX. AFTER WELD)

.729

.120 DIA.

.257

.324 (.352 MAX. AFTER WELD)

.662

COPPER

.090 REF.

KOVAR

.238 ±.010/.013

.150

.050

.010 ± .002

.051/.048 DIA.

.494/.478

FIGURE 23A

-34-

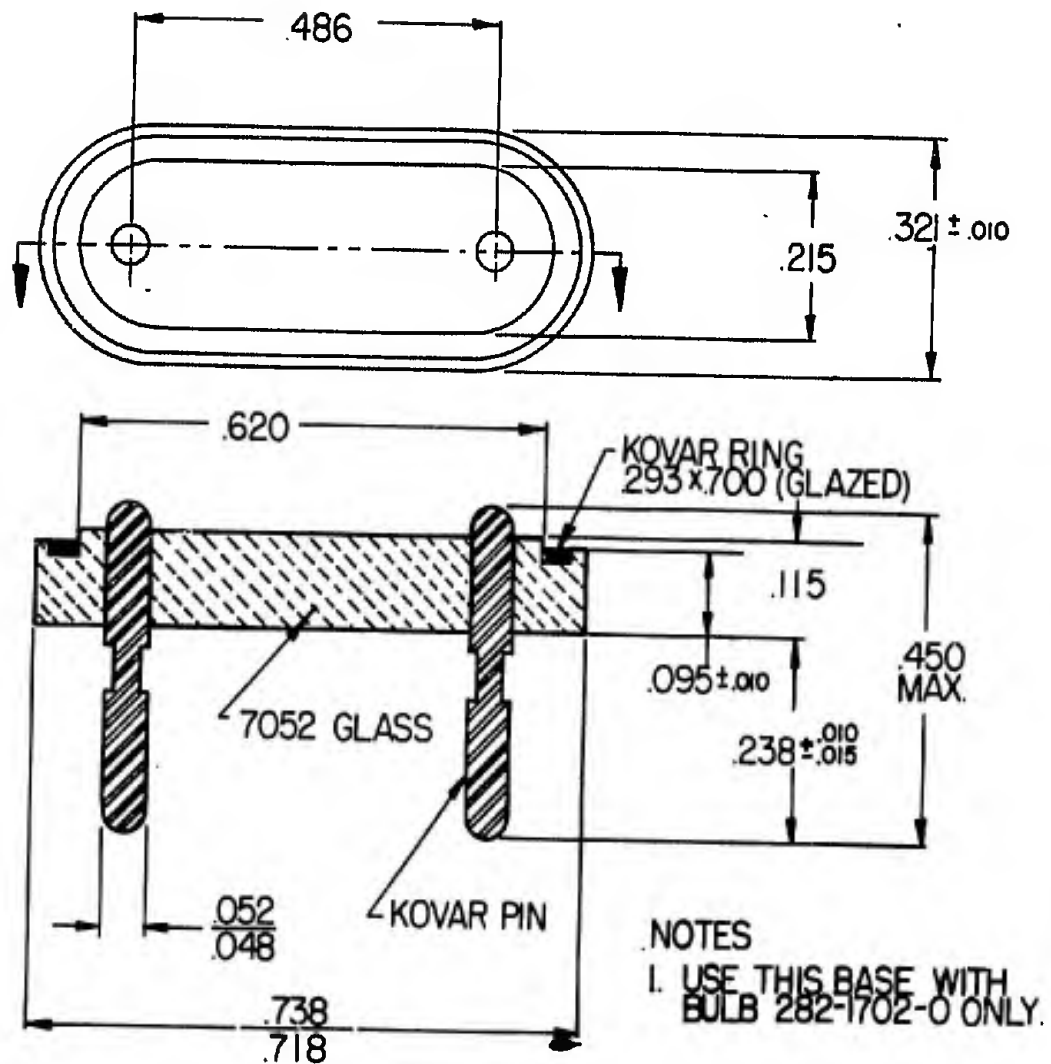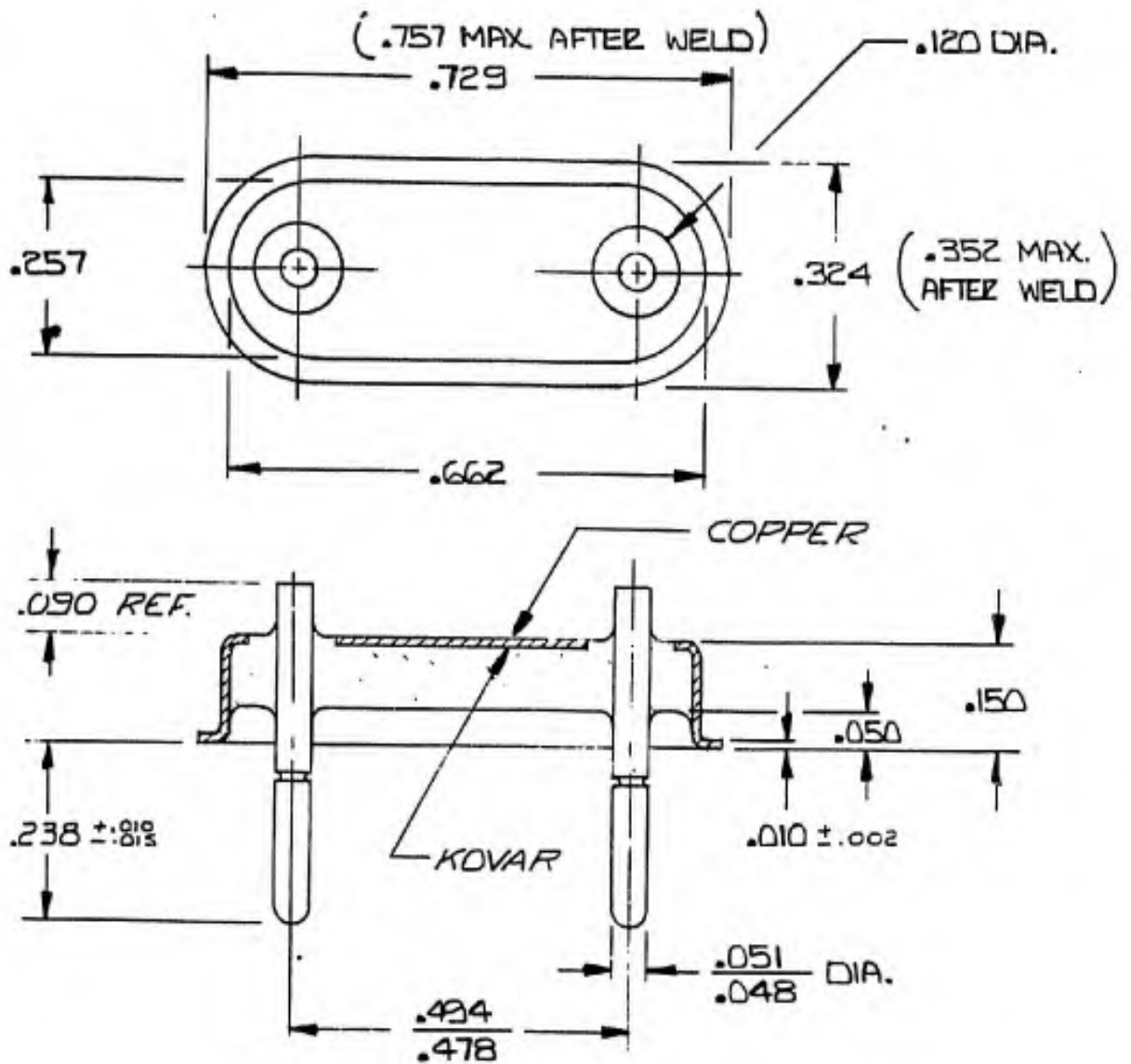**FIGURE 23B**

TCXO CRYSTAL SPECIFICATIONS

Group I-B (HC-26/U)

1. Operating Characteristics

   Frequency: 5 MC
   Cut and Mode: AT Fundamental
   Holder: HC-26/U
   Load Capacity: 32 pf
   Drive Level: 200 micro amps
   Calibration Tolerance and Temperature:
   $\pm$ 3 PPM at 30°C
   Operating Tolerance and Range: -40 to +80°C
   LTP-UTP: 20 PPM $\pm$ 5 PPM
   Unwanted Modes: $\pm$ 15 db
   Drive Stability: 1×10^{-9}/db
   Stability, Long Term: 1×10^{-8}/week at 60°C

2. Parameters

   C_0: 2.0pf max
   C_0/C_m: 300 $\pm$ 10%
   Resistance: $\pm$40 ohms max.
   Q: 1.6×10^5

3. Environmental

   Shock: 50G, 11 ms, 3planes
   Vibration: 20G, 50 to 2000 cps, 3 planes

4. Processing Specifications

   Diameter: .325"
   Quartz: Natural
   Contour: 10 diop Plano-convex
   Angle: AT 35° 11' to 35° 13'
   Electrical Diameter: 130

.083 2.

ZONE B

ZONE C

.460 ±.005

1/16" ZONE A

.418 ±.010

WALL THICKNESS .022-.028
WITH LIMITS

ZONE A .017-.033
" B .030-.045
" C .010-.040

.166 ±.010

FIGURE 24 A
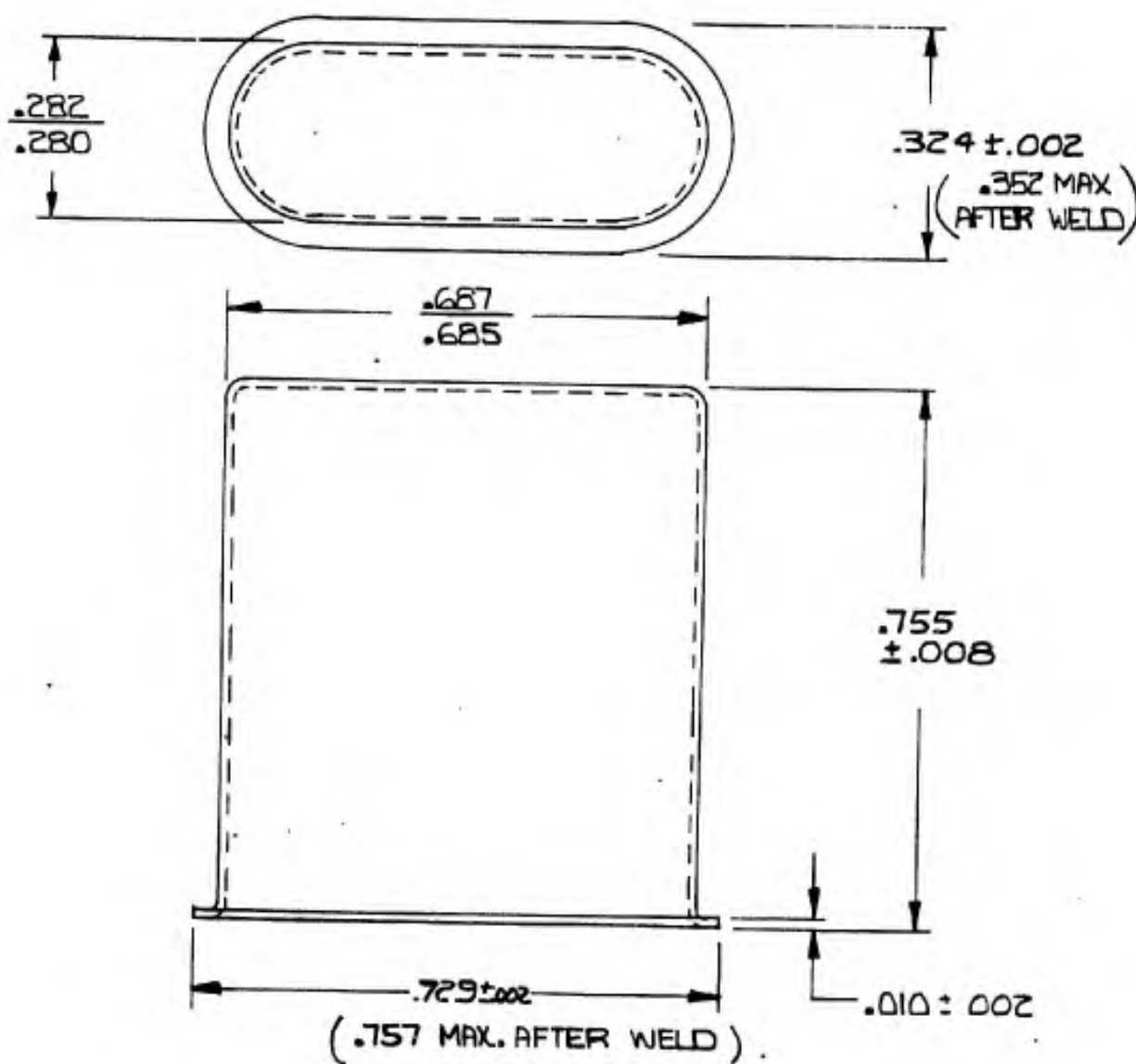
-37-

FIGURE 24B

TCXO CRYSTAL SPECIFICATIONS

Group I-B   (HC-18/U Type Coldweld)

1. Operating Characteristics

    Frequency: 5 MC
    Cut and Mode: AT Fundamental
    Holder: HC-18/U Coldweld
    Load Capacity: 32 pf
    Drive Level: 200 micro amps
    Calibration Tolerance and Temperature:
                $\pm$ 3 PPM at 30°C
    Operating Tolerance and Range: -40 to +80°C
    LTP-UTP: 20 PPM + 5 PPM
    Unwanted Modes: $\pm$15 db
    Drive Stability: 1×10^{-9}/db
    Stability, Long Term: 1×10^{-8}/week at 60°C

2. Parameters

    C_o: 2.0 pf max.
    C_o/C_m: 300 + 10%
    Resistance: $\pm$40 ohms max.
    Q: 1.6×10^5 min.

3. Environmental

    Shock: 50G, 11 ms, 3 planes
    Vibration: 20G, 50 to 2000 cps, 3 planes

4. Processing Specifications

    Diameter: .325"
    Quartz: Natural
    Contour: 10 diop Plano-convex
    Angle: AT 35° 11' to 35° 13'
    Electrical Diameter: 130
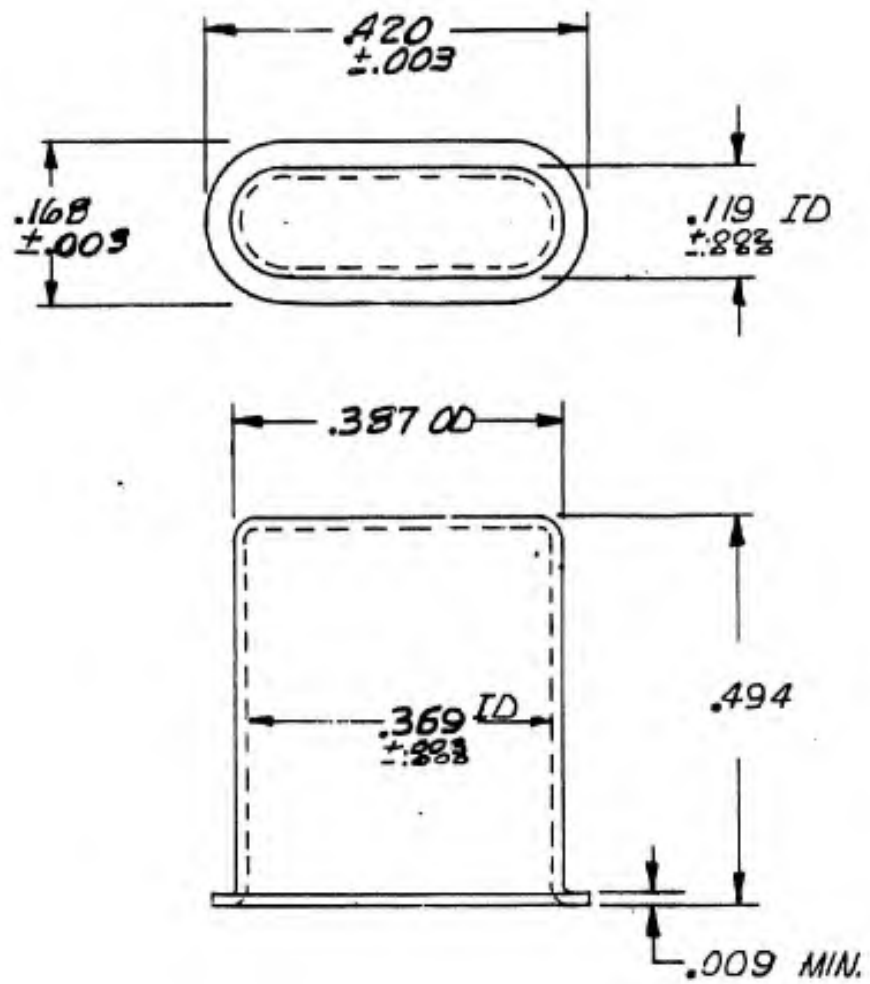
FIGURE 25A

FIGURE 25B

TCXO CRYSTAL SPECIFICATIONS

Group II - (HC-26/U)

1. Operating Characteristics

    Frequency: 5 MC
    Cut and Mode: AT Fundamental
    Holder: HC-26/U
    Load Capacity: 32 pf
    Drive Level: 200 micro amps
    Calibration Tolerance and Temperature:
    $\pm$ 3 PPM at 30°C
    Operating Tolerance and Range: -40 to +80°C
    LTP-UTP: 15 PPM + 5 PPM
    Unwanted Modes: -15 db
    Drive Stability: 1 x 10^{-9}/db
    Stability, Long Term: 1 x 10^{-8}/week at 60°C

2. Parameters

    C_o: 2.0 pf max.
    C_o/C_m: 300 $\pm$ 10%
    Resistance: -40 ohms max.
    Q: 1.6 x 10^5 min.

3. Environmental

    Shock: 50G, 11 ms, 3 planes
    Vibration: 20G, 50 to 2000 cps, 3 planes

4. Processing Specifications

    Diameter: .325"
    Quartz: Natural
    Contour: 10 diop Plano-convex
    Angle: AT 35° 11' to 35° 13'
    Electrical Diameter: 130
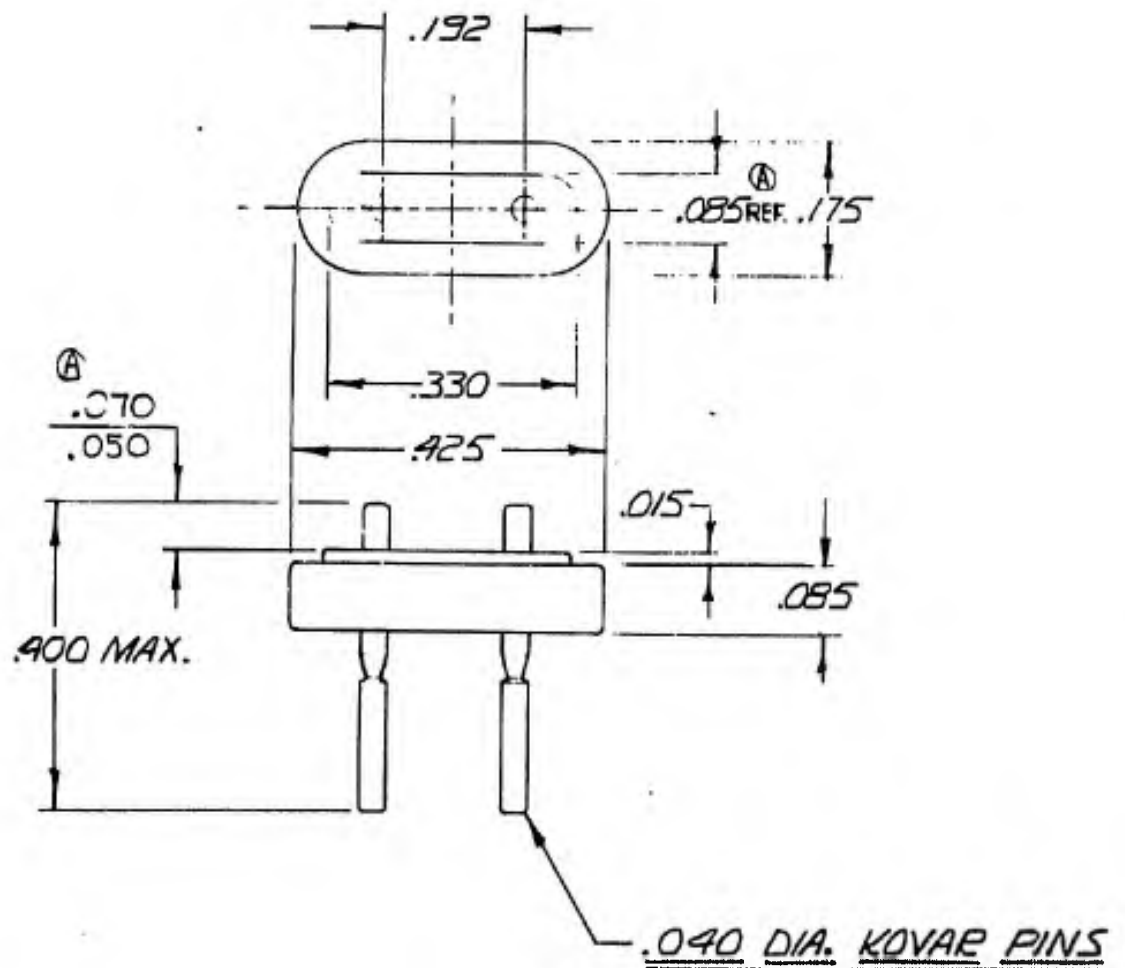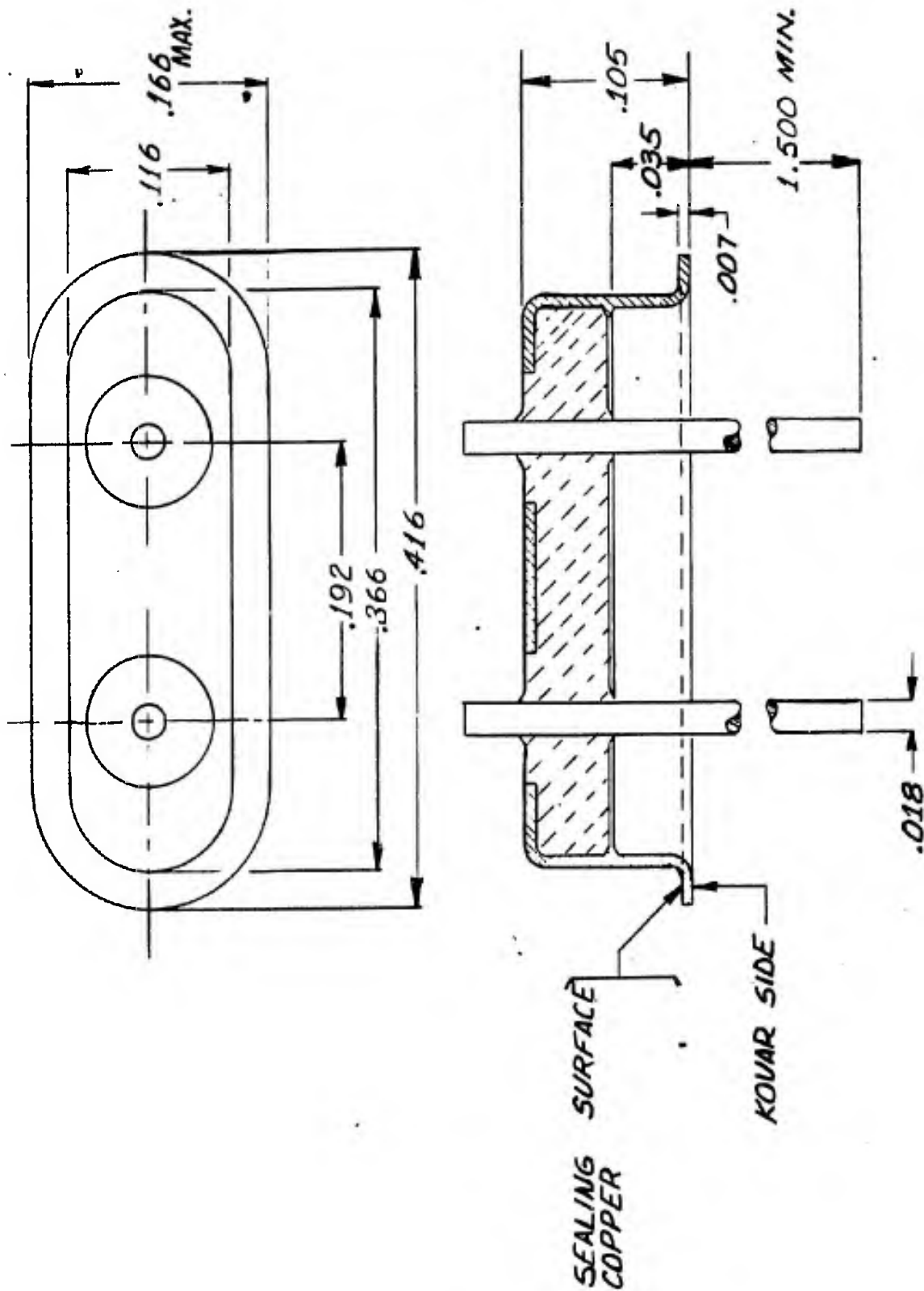
TCXO CRYSTAL SPECIFICATIONS

Group II - (HC-18/U Type Coldweld)

1. Operating Characteristics

   Frequency: 5 MC
   Cut and Mode: AT Fundamental
   Holder: HC-18/U Coldweld
   Load Capacity: 32 pf
   Drive Level: 200 micro amps
   Calibration Tolerance and Temperature:
                $\pm$ 3 PPM at 30°C
   Operating Tolerance and Range: -40°C to +80°C
   LTP-UTP: 15 PPM $\pm$ 5 PPM
   Unwanted Modes: $-$15 db
   Drive Stability: 1×10^{-9}/db
   Stability, Long Term: 1×10^{-8}/week at 60°C

2. Parameters

   C_0: 2.0 pf max.
   C_0/C_m: 300 $\pm$ 10%
   Resistance: $-$40 ohms max.
   Q: 1.6×10^5

3. Environmental

   Shock: 50G, 11 ms, 3 planes
   Vibration: 20G, 50 to 2000 cps, 3 planes

4. Processing Specifications

   Diameter: .325"
   Quartz: Natural
   Contour: 10 Diop Plano-convex
   Angle: AT 35° 11' to 35° 13'
   Electrical Diameter: 130

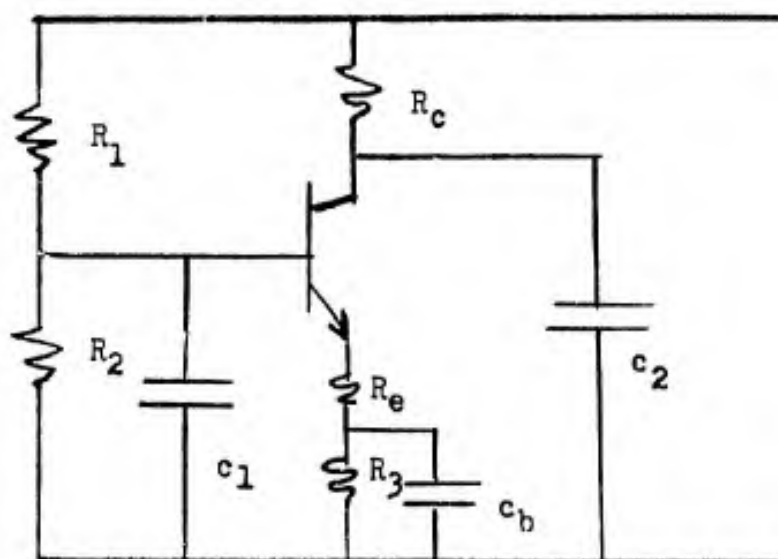# Ungrounded Emitter Pierce Oscillator Analysis.

Circuit Diagram

FIGURE 26

Assume 1. $X_{cb} << R_3$ $X_{cb} \approx 0$

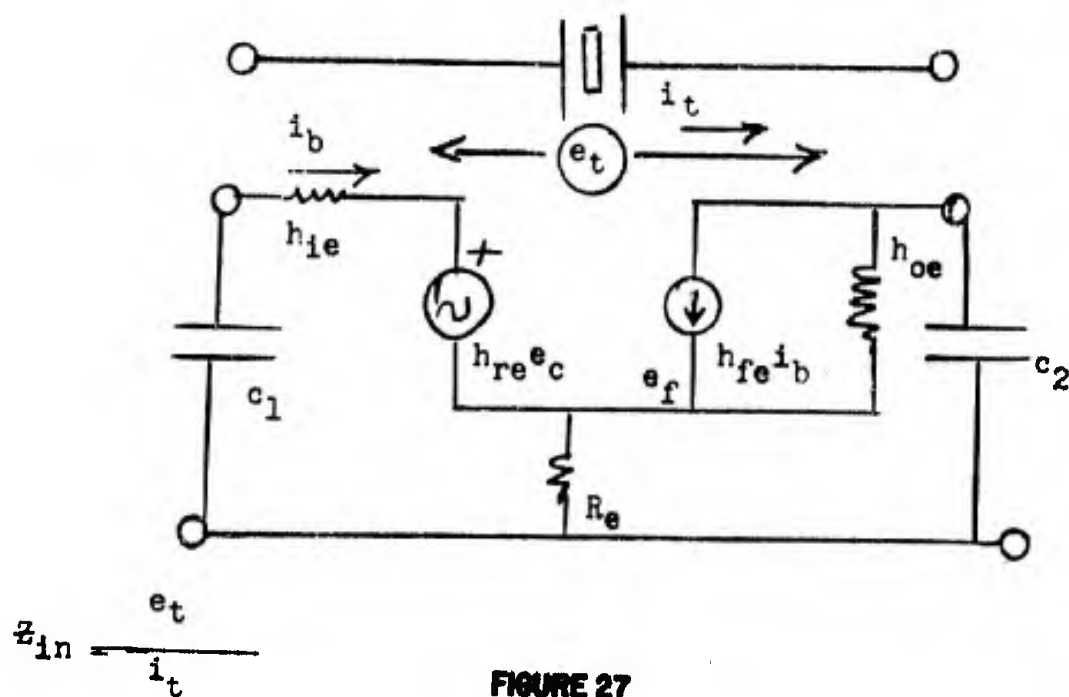2. $X_{c2} << R_c$

3. $X_{c1} << \dfrac{R_1 R_2}{R_1 + R_2}$

$$z_{in} = \frac{e_t}{i_t}$$

FIGURE 27

1. $\dfrac{e_b}{-jx_1} + \dfrac{e_b - h_{re}e_c - e_f}{h_{ie}} + i_t = 0$

2. $\dfrac{e_f}{R_e} + \dfrac{e_f + h_{re}e_c - e_b}{h_{ie}} + \dfrac{e_f - e_c}{1/h_{oe}} - h_{fe}i_b = 0$

3. $\dfrac{e_c}{-jx_2} + \dfrac{e_c - e_f}{1/h_{oe}} + h_{fe}i_b + i_t = 0$

4. $e_c - e_b = e_t$

   $-e_b = e_t - e_c$

   $e_b = e_c - e_t$

1. $\dfrac{e_c - e_t}{-jx_1} + \dfrac{e_c(1-h_{re}) - e_t - e_f}{h_{ie}} + i_t = 0$

2. $\dfrac{e_f}{R_e} + \dfrac{e_f + e_t - e_c(1-h_{re})}{h_{ie}} + \dfrac{e_f - e_c}{1/h_{oe}} - h_{fe}i_b = 0$

3. $\dfrac{e_c}{-jx_2} + \dfrac{e_c - e_f}{1/h_{oe}} + h_{fe}i_b + i_t = 0$

   since $i_b = \dfrac{e_b - h_{re}e_c - e_f}{h_{ie}}$

   $e_b = e_c - e_t$

   $i_b = \dfrac{e_c(1-h_{re}) - e_t - e_f}{h_{ie}}$

2. $\dfrac{e_f}{R_e} + \dfrac{e_f + e_t - e_c(1-h_{re})}{h_{ie}} + \dfrac{e_f - e_c}{1/h_{oe}} - \dfrac{h_{fe}}{h_{ie}}\left(e_c(1-h_{re}) - e_t - e_f\right) = 0$

3. $\dfrac{e_c}{-jx_2} + \dfrac{e_c - e_f}{1/h_{oe}} + \dfrac{h_{fe}}{h_{ie}}\left(e_c(1-h_{re}) - e_t - e_f\right) + i_t = 0$

Ungrounded Emitter Pierce Oscillator Analysis, continued

1. $e_c \left[\dfrac{1}{-jx_1} + \dfrac{(1-h_{re})}{h_{ie}} \right] + e_f \left[-\dfrac{1}{h_{ie}} \right] + e_t \left[\dfrac{1}{jx_1} - \dfrac{1}{h_{ie}} \right] = i_t$

2. $e_c \left[\dfrac{-(1-h_{re})}{h_{ie}} - h_{oe} - \dfrac{h_{fe}(1-h_{re})}{h_{ie}} \right] + e_f \left[\dfrac{1}{R_e} + \dfrac{1}{h_{ie}} + h_{oe} + \dfrac{h_{fe}}{h_{ie}} \right]$

$+ e_t \left[\dfrac{1}{h_{ie}} + \dfrac{h_{fe}}{h_{ie}} \right] = 0$

3. $e_c \left[\dfrac{1}{-jx_2} + h_{oe} + \dfrac{h_{fe}(1-h_{re})}{h_{ie}} \right] + e_f \left[-h_{oe} - \dfrac{h_{fe}}{h_{ie}} \right]$

$+ e_t \left[-\dfrac{h_{fe}}{h_{ie}} \right] = i_t$

Colpitt's Oscillator Analysis
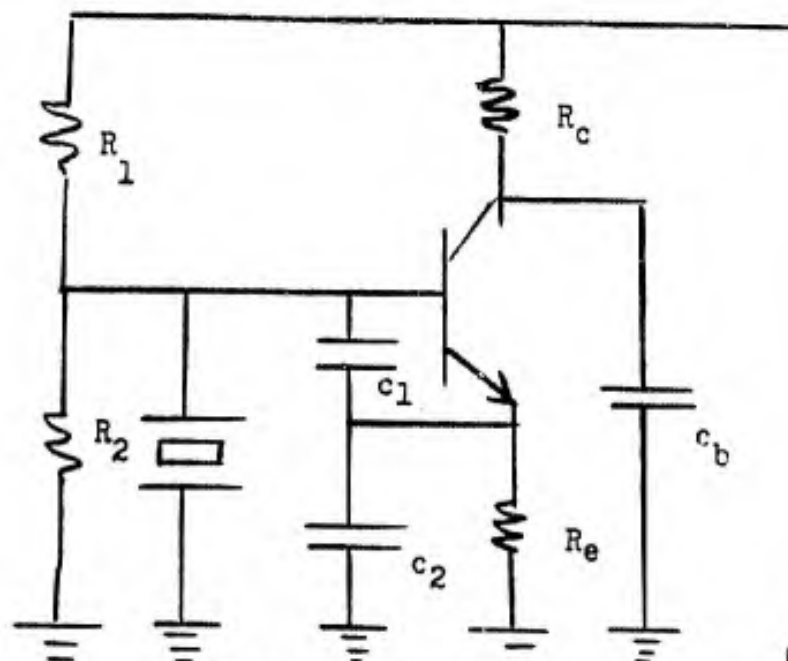
Circuit Diagram

FIGURE 28

Assume: 1. $X_{cb} \approx 0$ $X_{cb} << R_c$

2. $?(X_{c_1} + X_{c_2}) << \dfrac{R_1 R_2}{R_1 + R_2}$
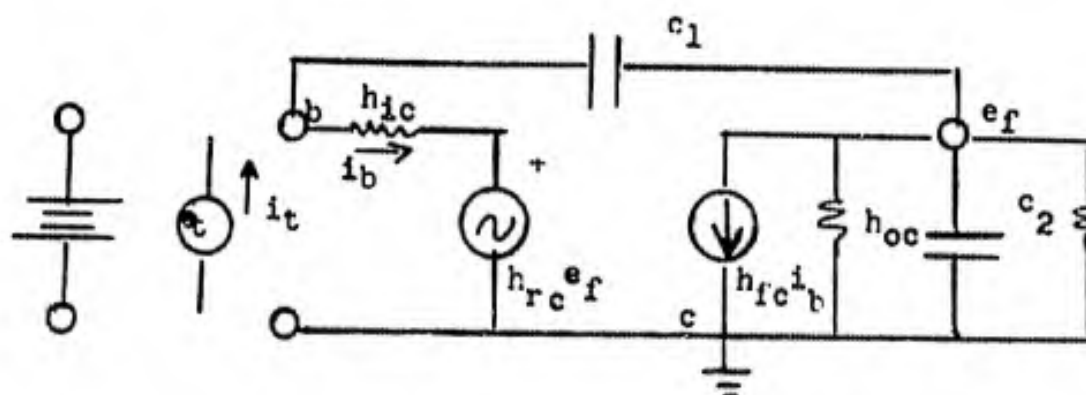
Equivalent Circuit

FIGURE 29

$$z_{in} = \frac{e_t}{i_t}$$

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Colpitt's Oscillator Analysis, continued

1. $\dfrac{e_b - h_{rc}e_f}{h_{ic}} + \dfrac{e_b - e_f}{-jx_1} = +i_t$

2. $\dfrac{e_f}{-jx_2} + \dfrac{e_f}{1/h_{oc}} + h_{fc}i_b + \dfrac{e_f - e_b}{-jx_1} = 0$

$i_b = \dfrac{e_b - h_{rc}e_f}{h_{ic}}$

2. $\dfrac{e_f}{-jx_2} + \dfrac{e_f}{1/h_{oc}} + \dfrac{h_{fc}}{h_{ic}}\left\{e_b - h_{rc}e_f\right\} + \dfrac{e_f - e_b}{-jx_1} = 0$

1. $e_b\left\{\dfrac{1}{h_{ic}} + \dfrac{1}{-jx_1}\right\} + e_f\left\{\dfrac{-h_{rc}}{h_{ic}} + \dfrac{1}{jx_1}\right\} = +i_t$

2. $e_b\left\{\dfrac{1}{jx_1} + \dfrac{h_{fc}}{h_{ic}}\right\} + e_f\left\{\dfrac{1}{-jx_2} + h_{oc} - \dfrac{h_{fc}h_{rc}}{h_{ic}} + \dfrac{1}{-jx_1}\right\} = 0$

$$\Delta = \left|\begin{array}{cc} \left[\dfrac{1}{h_{ic}} + j\dfrac{1}{x_1}\right] & \left[\dfrac{-h_{rc}}{h_{ic}} - j\dfrac{1}{x_1}\right] \\[3ex] \left[\dfrac{h_{fc}}{h_{ic}} - j\dfrac{1}{x_1}\right] & \left[h_{oc} - \dfrac{h_{fc}h_{rc}}{h_{ic}} + j\left(\dfrac{1}{x_2} + \dfrac{1}{x_1}\right)\right] \end{array}\right|$$

$$N_{e_b} = N_{e_t} = \left|\begin{array}{cc} +i_t & \left[\dfrac{-h_{rc}}{h_{ic}} - j\dfrac{1}{x_1}\right] \\[3ex] 0 & \left[h_{oc} - \dfrac{h_{fc}h_{rc}}{h_{ic}} + j\left(\dfrac{1}{x_2} + \dfrac{1}{x_1}\right)\right] \end{array}\right|$$

$$Z_{in} = \frac{(+1)\left[h_{oc} - \dfrac{h_{fc}h_{rc}}{h_{ic}} + j\left(\dfrac{1}{x_1} + \dfrac{1}{x_2}\right)\right]}{\left[\dfrac{1}{h_{ic}} + j\dfrac{1}{x_1}\right]\left[h_{oc} - \dfrac{h_{fc}h_{rc}}{h_{ic}} + j\left(\dfrac{1}{x_1} + \dfrac{1}{x_2}\right)\right] - \left[\dfrac{h_{fc}}{h_{ic}} - j\dfrac{1}{x_1}\right]\left[-\dfrac{h_{rc}}{h_{ic}} - j\dfrac{1}{x_1}\right]}$$

$$y \longrightarrow h \qquad \text{Transformation's Common Collector}$$

$$h_{ic} = \frac{1}{y_{ie}}$$

$$h_{rc} = 1 - \frac{y_{re}}{y_{ie}}$$

$$h_{fc} = -\left\{1 + \frac{y_{fe}}{y_{ie}}\right\}$$

$$h_{o,c} = y_{oe}$$

$$Z_{in_{y's}} = \frac{y_{oe} + y_{ie} + y_{fe} - y_{re} - \dfrac{y_{fe}y_{re}}{y_{ie}} + j\left(\dfrac{1}{x_1} + \dfrac{1}{x_2}\right)}{\left[y_{ie} + j\dfrac{1}{x_1}\right]\left[y_{oe} + y_{ie} + y_{fe} - y_{re} - \dfrac{y_{fe}y_{re}}{y_{ie}} + j\left(\dfrac{1}{x_1} + \dfrac{1}{x_2}\right)\right] + \left[y_{ie} + y_{fe} - j\dfrac{1}{x_1}\right]\left[y_{re} - y_{ie} - j\dfrac{1}{x_1}\right]}$$
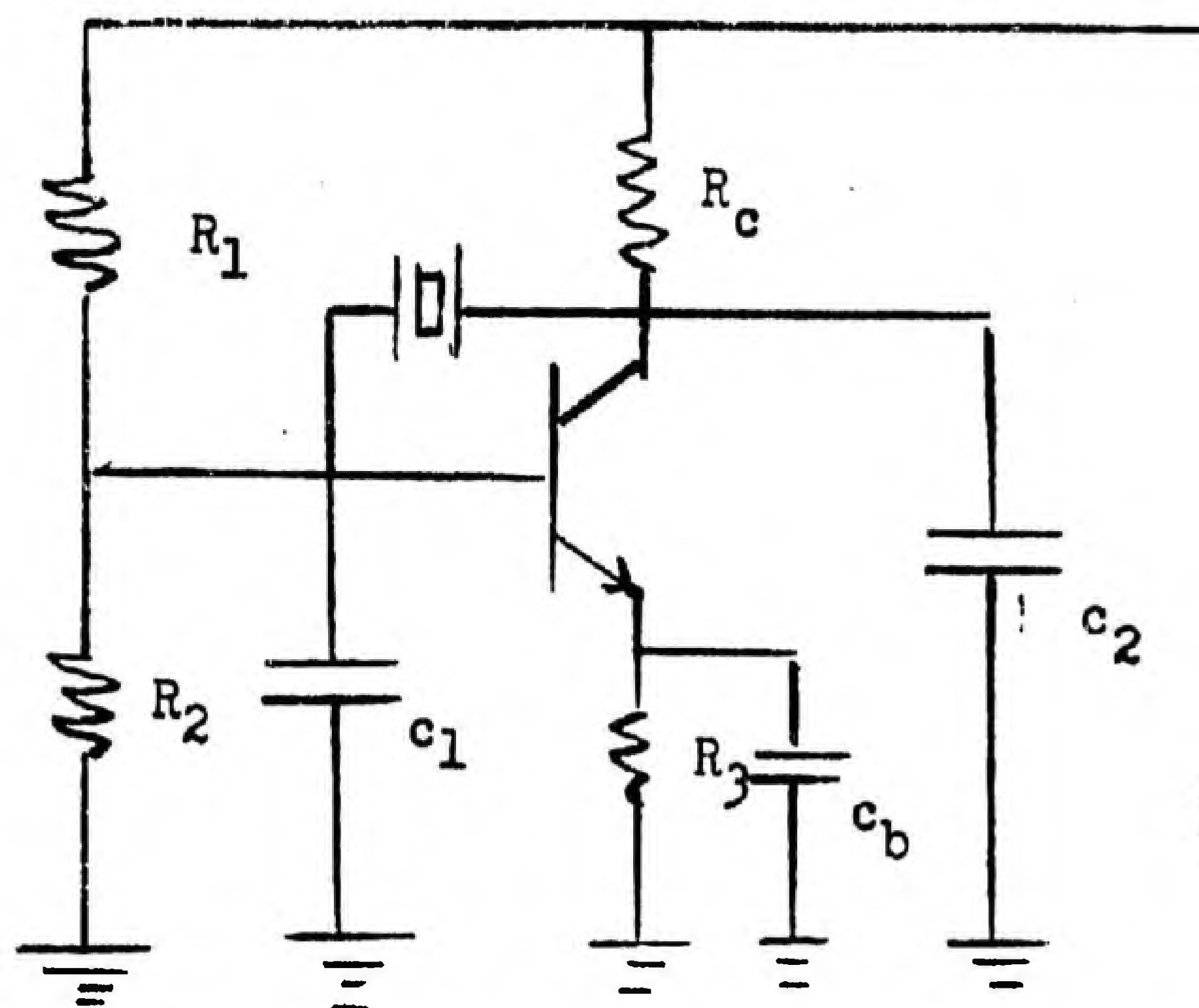
Grounded Emitter Pierce Oscillator Analysis.

Circuit Diagram

Assume: 1. c_b effective by pass

2. $X_{c_2} << R_c$

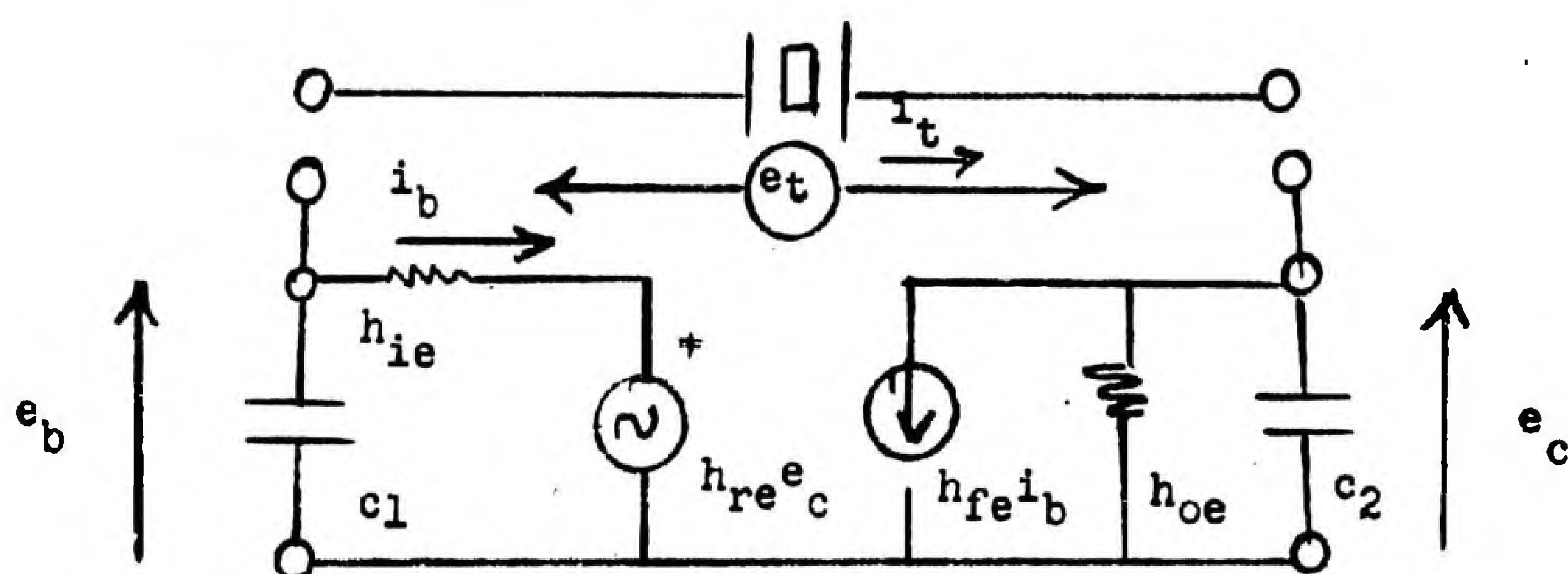3. $X_{c_1} << \dfrac{R_1 R_2}{R_1 + R_2}$

Equivalent Circuit

FIGURE 31

$$z_{in} = \frac{e_t}{i_t}$$

1. $\dfrac{e_b}{-jx_1} + \dfrac{e_b - h_{re}e_c}{h_{ie}} + i_t = 0$

2. $\dfrac{e_c}{-jx_2} + e_c h_{oe} + h_{fe} i_b + i_t = 0$

$$e_c = e_b + e_t$$

$$e_b = e_c - e_t$$

Then

1. $\dfrac{e_c}{-jx_1} - \dfrac{e_t}{-jx_1} + \dfrac{e_c (1-h_{re}) -e_t}{h_{ie}} = i_t$

2. $\dfrac{e_c}{-jx_2} + e_c h_{oe} + h_{fe} i_b = i_t$

$$i_b = \dfrac{e_b - h_{re} e_c}{h_{ie}}$$

$$= \dfrac{e_c - e_t - h_{re}e_c}{h_{ie}}$$

$$= \dfrac{(1-h_{re}) e_c - e_t}{h_{ie}}$$

2. $\dfrac{e_c}{-jx_2} + e_c h_{oe} + \dfrac{h_{fe}}{h_{ie}}\left\{(1-h_{re}) e_c - e_b\right\} = - i_t$

1. $e_t\left\{\dfrac{1}{jx_1} - \dfrac{1}{h_{ie}}\right\} + e_c\left\{\dfrac{1}{-jx_1} + \dfrac{(1-h_{re})}{h_{ie}}\right\} = - i_t$

2. $e_t\left\{\dfrac{-h_{fe}}{h_{ie}}\right\} + e_c\left\{\dfrac{1}{-jx_2} + h_{oe} + \dfrac{h_{fe}}{h_{ie}}(1-h_{re})\right\} = - i_t$

Grounded Emitter Pierce Oscillator Analysis, continued

$$e_t = \cfrac{\left| \begin{array}{c} -i_t\left[\dfrac{1}{-jx_1} + \dfrac{(1-h_{re})}{h_{ie}}\right] \\[4mm] -i_t\left[\dfrac{1}{-jx_2} + h_{oe} + \dfrac{h_{fe}}{h_{ie}}(1-h_{re})\right] \end{array} \right|}{\left| \begin{array}{c} \left[\dfrac{1}{jx_1} - \dfrac{1}{h_{ie}}\right]\left[\dfrac{1}{-jx_1} + \dfrac{(1-h_{re})}{h_{ie}}\right] \\[4mm] \left[-\dfrac{h_{fe}}{h_{ie}}\right]\left[\dfrac{1}{-jx_2} + h_{oe} + \dfrac{h_{fe}}{h_{ie}}(1-h_{re})\right] \end{array} \right|}$$

$$e_t = \cfrac{-i_t\left[\ \ \right] + i_t\left[\ \ \right]}{\left[\ \ \right]\left[\ \ \right] - \left[\ \ \right]\left[\ \ \right]}$$

$$z_{in} = \cfrac{\left[\ \ \right] - \left[\ \ \right]}{\left[\ \ \right]\left[\ \ \right] - \left[\ \ \right]\left[\ \ \right]}$$

$$= \cfrac{\left[\dfrac{1}{-jx_1} + \dfrac{(1-h_{re})}{h_{ie}}\right] - \left[\dfrac{1}{-jx_2} + h_{oe} + \dfrac{h_{fe}}{h_{ie}}(1-h_{re})\right]}{\triangle}$$

Grounded Emitter Pierce Oscillator Analysis, continued

$$\triangle_h = \frac{1}{+jx_1}\frac{1}{h_{ie}}\frac{1}{-jx_2} + h_{oe} + \frac{h_{fe}}{h_{ie}}(1-h_{re}) - \frac{-h_{fe}}{h_{ie}}\frac{1}{-jx_1} + \frac{(1-h_{re})}{h_{ie}}$$

$y \longrightarrow h$ Transformation's Common Emitter

$$h_{ie} = \frac{1}{y_{ie}}$$

$$h_{re} = \frac{y_{re}}{y_{ie}}$$

$$h_{fe} = \frac{y_{fe}}{y_{ie}}$$

$$h_{oe} = y_{oe}$$

Substituting

$$\triangle_{y_s} = \left[\frac{1}{+jx_1} - y_{ie}\right]\left[\frac{1}{-jx_2} + y_{oe} + \frac{y_{fe}}{1}(1-\frac{y_{re}}{y_{ie}})\right] + \left[y_{fe}\right]\left[\frac{1}{-jx_1} + y_{ie}(1-\frac{y_{re}}{y_{ie}})\right]$$

$$\triangle_{y_s} = \left[\frac{1}{jx_1} - y_{ie}\right]\left[\frac{1}{-jx_2} + y_{oe} + y_{fe}(1-\frac{y_{re}}{y_{ie}})\right] + \left[y_{fe}\right]\left[\frac{1}{-jx_1} + y_{ie} - y_{re}\right]$$

$$\triangle_{y_s} = \left[-jy_1 - y_{ie}\right]\left[+jy_2 + y_{oe} + y_{fe} - \frac{y_{fe}y_{re}}{y_{ie}}\right]$$
$$+ \left[+jy_{fe}y_1 + y_{fe}y_{ie} - y_{fe}y_{re}\right]$$

Grounded Emitter Pierce Oscillator Analysis, continued

$${}^N y_{z_{in}} = \left[\frac{1}{-jx_1} + y_{ie}\left(1-\frac{y_{re}}{y_{ie}}\right)\right]\left[\frac{1}{-jx_2} + y_{oe} + \frac{\frac{y_{fe}}{y_{ie}}}{\frac{1}{y_{ie}}}\left(1-\frac{y_{re}}{y_{ie}}\right)\right]$$

$$= \left[\frac{1}{-jx_1} + y_{ie} - y_{re}\right]$$

$$- \left[\frac{1}{-jx_2} + y_{oe} + y_{fe}\left(1-\frac{y_{re}}{y_{ie}}\right)\right]$$

$$= \left[y_{ie} - y_{re} + jy_1\right] - \left[y_{oe} + y_{fe}\left(1-\frac{y_{re}}{y_{ie}}\right) + jy_2\right]$$

$$z_{in} = \frac{\left[y_{ie} - y_{re} + jy_1\right] - \left[y_{oe} + y_{fe}\left(1-\frac{y_{re}}{y_{ie}}\right) + jy_2\right]}{\left[-jy_1 - y_{ie}\right]\left[+jy_2 + y_{oe} + y_{fe} - \frac{y_{fe}\,y_{re}}{y_{ie}}\right] + \left[+j\,y_{fe}\,y_1 + y_{fe}\,y_{ie} - y_{fe}\,y_{re}\right]}$$

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13. ABSTRACT

This report discussed the results of the investigation for the first six months of the contract. A new concept in compensation circuitry has been borrowed from analog computer non-linear function generator theory and is being utilized in an effort to make the compensation process automatic.

Automatic compensation equipment has been investigated and a complete automatic compensator is currently being constructed.

Thermal transient characteristics have been analyzed, and some empirical data taken.

Several oscillator circuits have been analyzed.

Crystal specifications for 2×10^{-7} and 5×10^{-8} type resonators have been developed.

DD FORM 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Temperature compensated oscillators						
Automatic compensation equipment for temperature compensated oscillators.						