RESEARCH AND DEVELOPMENT TECHNICAL REPORT
ECOM-0301-F

TACTICAL MINIATURE CRYSTAL OSCILLATOR

FINAL REPORT
by
April 1973

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UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.
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Engineering Experiment Station
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia 30332
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TACTICAL MINIATURE CRYSTAL OSCILLATOR

Final Report

July 1, 1971 to August 30, 1972

Contract No. DAAB07-71-C-0301
DA Project No. 1H6 62705 A 058 0306

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Prepared by
Engineering Experiment Station
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For
U. S. Army Electronics Command
Fort Monmouth, New Jersey
ABSTRACT

The purpose of this work was to develop an experimental tactical miniature crystal oscillator (TMXO) in a 5 in³ volume, use < 10 W warmup power from -40°C to +85°C in 1 min, and then operate on < 250 mW. It was to reach a maximum deviation from final frequency of ± 1 X 10⁻⁷ after a 1 min period. The short term stability requirement was to have a maximum rms frequency deviation of ± 1 X 10⁻¹¹ for averaging times from 1 sec to 20 min.

The TMXO assembly was housed in a stainless steel vacuum container. The temperature sensitive components, i.e., resonator, oscillator and temperature controller, were mounted in the isothermal region of this container. The MOSFET crystal-controlled oscillator and the temperature controller were hybrid microcircuits. Both these circuits and a heating element were epoxy bonded to the resonator can. The temperature sensitive components were insulated from external temperature ambients with aluminized mylar films. Outside the isothermal region was a voltage regulator and a micropotentiometer. The latter had outside access to adjust the frequency within ± 1 X 10⁻⁸.

The overall design concept, while not especially successful in meeting all the performance criteria, did indicate the potential and suitability of this design for constructing TMXO's. Only the goal regarding volume has been met on all models. On different models, however, the guideline requirements have also been met for frequency/load stability, frequency/voltage stability, frequency adjustment and output voltage. Data have been presented which show that both power and frequency requirements could be met, given low pressure operating conditions and improved techniques to fabricate vacuum compatible hybrid microcircuits.
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The technical guidelines for the development of a Tactical Miniature Crystal Oscillator (TMXO) call for a fast warm-up OCXO to be developed with temperature control encapsulated in a hermetically sealed enclosure, and with the maximum use made of integrated circuitry techniques.

A general design concept for this TMXO was described in the interim report\(^1\) which was submitted at the end of Phase I of this contract. This design concept has generally been followed with certain changes being made during the course of the work to either improve the initial design or correct defects in it.

As reported in the semiannual report\(^2\) parts of the oscillator circuitry had been changed to enable metal oxide semiconductor field-effect transistors (MOSFET) to be used. This device is the solid-state equivalent of a vacuum tube, requires no signal driving power and may be designed to have a signal-leveling effect (AGC).

The temperature sensitive gain feature of the temperature control circuit was eliminated, since experiments showed that a carefully selected, fixed-gain condition was preferred. Positioning and method of attachment of the temperature sensing and control elements of the temperature control circuit were found to have a definite effect on the short-term stability of the entire system.

After experiencing a high power requirement with TMXO Model No. 1, it was decided to replace the stainless-steel pedestal with one made of VESPEL® (polyimide). The method of supporting the stainless-steel screen, which surrounds the crystal and circuit boards, was also modified. In Model No. 1, this screen was attached to the main base of the TMXO with four stainless-steel wires, which were also a source of heat-loss. In later models this supporting system was replaced by a supporting attachment on the VESPEL pedestal. This screen was found to be necessary in order to eliminate the capacitive coupling effect which was experienced between the exposed circuit boards and the NRC-2 insulating material.

As the technical data presented in this report will show, the performance goals which are outlined in the abstract were, in general, not met when applied to any one of the three exploratory development models. However, the evaluation studies performed on the three models and associated sub-assemblies have demonstrated that the basic TMXO design is sound. With suitable improvements in fabrication techniques, particularly in the areas of microcircuits and vacuum compatibility, the desired working model can be manufactured.
II. DESIGN FEATURES

A. Mechanical Construction

1. Vacuum Vessel

The suggested design of the TMXO enclosure in the proposal was an evacuated double-wall, NRC-2 insulated, stainless-steel, dewar-type vessel. During phase I of this contract, it became apparent that the interior wall of such a vessel represented an intolerable heat load unless the interior of the enclosure was evacuated and the isothermal region thoroughly insulated. If, however, the latter was done, the need for a double-wall dewar was eliminated.

The original package for Model No. 1, as described in Report TR ECOM-0301 (interim) consisted of a type-D, cold-weld holder about three inches tall. Figure 1 shows the general arrangement of the parts within the enclosure. The resonator and associated electronic circuits are mounted on a stainless-steel pedestal spot-welded to the type-D header. The center of the pedestal is hollow to reduce the cross section of heat-conducting material and also to serve as a shield for the RF output lead.

The components mounted on the base are the frequency-trimming potentiometer and the voltage regulator. Neither of these items is in the isothermal region, but calculations have shown that neither of them needs to be at constant temperature during operation of the device. A plan view of the layout for the parts mounted on the header is shown by Fig. 2, and a photograph of the mounted components is shown in Fig. 3.

The extended type-D holder, shown in Fig. 4, was made by cutting the standard one-half inch high holder into two pieces and inserting a suitable length of stainless-steel tubing. The parts were soldered together with ALL STATE #430 soft silver solder (melting point 430°F), since welding the very thin walls proved both costly and unreliable.

After TMXO Model No. 1 was completely assembled and sealed by cold-welding it was discovered (from power consumption measurements) that the can was not vacuum tight. A visual inspection of the cold-welded flange revealed that about 25% of the indentation was not welded. Additional work to the die did not alleviate the problem and the die had to be abandoned.

After a telephone discussion with the Contracting Officer's Technical Representative, it was decided to fabricate a new base for this unit from stainless steel and hard solder in three high temperature electrical feed-throughs. This base was then soldered to the can with CERROSEAL-35** (Sn-In Solder). This change in our method of fabrication necessitated attaching a copper pump-out tube since the stainless-steel base could not be cold-welded to the can. A pinch-off tool was used to seal the pump-out tube and disconnect the unit from the vacuum system.

The location of the components on the new base was not changed significantly from that shown in Fig. 2.

---

* All State Welding Alloy Co., White Plains, N. Y.
** Product of the Cerro Corporation, New York.
HC-6 Cold-weld holder & 5 MHz crystal

Temperature control unit on alumina chip.

HC-6/U holder.

Frequency trimming potentiometer Bourns No. 3280L (50K)

Temperature control transistor and thermistor

Wrap-around heater on HC-6 cap.

Crystal oscillator mounted on alumina wafer.

Stainless steel pedestal.

External components for regulator potted in silicone rubber.

Voltage regulator Fairchild μA723 in TO-5 holder.

Not used.

SCALES: Vacuum Vessel Interior 2:1, Base Pins 1:1.

Fig. 1. Basic conceptual design of TMXO.
Fig. 2. Layout of components on the type "D" base.
Fig. 3. Photograph of Base Assembly.
Fig. 4. Photograph of Extended Type "D" Cap used for Model No. 1.
TMXO Models No. 2 and No. 3 were assembled on type-D bases with the pedestal attached to the base with VAC-SEAL* low vapor pressure resin epoxy. The pedestals were not spot-welded to the bases because during welding enough localized heat is generated to cause separation of the glass to metal seal around the electrical feedthroughs and subsequent leaking during evacuation attempts.

These bases could not be cold-welded to the extended type-D caps, due to the faulty die, so new caps were fabricated from stainless steel. Figure 5 shows the dimensions of the two-piece cap. The bases were then soldered to the main piece with CERROSEAL-35 (Sn-In Solder). The top piece was designed to be soldered to the main piece, in vacuum, after evacuation and bakeout were accomplished. This is done by heating a button heater, temporarily secured to the top piece, sufficiently to reflow the tinned surfaces as they were mated together by a manipulator which operated in the vacuum system.

The locations of the components on the bases of Models Nos. 2 and 3 are identical to those shown in Figs. 1 through 3.

2. Resonator Support

The design of the isothermal core support of Model No. 1 is shown in Fig. 6. The lower (round) flange is spot-welded to the custom stainless-steel base. The upper rectangular flange was designed for spot-welding the untrimmed sealing flange of the HC-6 crystal holder to it. However, the purchased crystal units were delivered in slim-line type holders which do not have the larger flange. The actual method of attaching the crystal unit was the following. A piece of alumina 7/16" X 3/8" was first attached to the upper pedestal flange with low-vapor pressure resin (TORR-SEAL**). Then the resonator assembly was attached with TORR-SEAL to the alumina. The alumina served a twofold purpose: firstly, to act as a heat barrier to inhibit the loss of heat from the crystal unit and secondly, to allow the option of operating the crystal can grounded or ungrounded (DC). The ungrounded mode of operation was chosen so that the control transistor chip, Q2, of the temperature control circuit could be attached directly to the top of the HC-6 crystal can for maximum heat transfer.

Models Nos. 2 and 3 were modified to incorporate a support made of a polyimide (VESPEL)*** material. Figure 7 shows the dimensions of this solid support rod in addition to the two stainless-steel end pieces. The reason for changing from a stainless-steel pedestal to one of VESPEL is to reduce the thermal losses through this support member. This is discussed in greater detail in Section II-A-5.

3. Location and Support of Electronic Circuits

The voltage regulator and frequency-trimming potentiometer are located on the base as described in Section II-A-1. In Models Nos. 2 and 3 the regulator is mounted on a 1/4" thick VESPEL pad which in turn is mounted to the base. This was done as an attempt to isolate the regulator from the full ambient temperature swing. Access to the screw adjustment of the trimpot is a hole through the base. The trimpot is mounted in a sealed HC-6/U

---

* Product of Perkin-Elmer, Ultek Division, Palo Alto, Calif.
** Varian Associates, Vacuum Division, Palo Alto, Calif.
*** E. I. du Pont de Nemours & Co., Wilmington, Del.
Fig. 5. Two-piece cap for Models Nos. 2 and 3.
Fig. 6. Stainless-steel support pedestal. Lower (round) end spot-welds to Model No. 1 base. Upper (rectangular) end attaches to HC-6 holder.
Fig. 7. Support pedestal assembly for TMXO Models Nos. 2 and 3.
holder which is sealed to the base over the access hole.

Both the temperature of the oscillator circuit and the temperature controlling circuit must be controlled. The precision to which this temperature is controlled need not be as great as that of the resonator, but the variation must certainly be far less than the anticipated 120°C ambient variation. In order to conserve power, we decided to use only one heater for both the crystal unit and the electronic circuits. The resonator heater* is an etched foil element encased in KAPTON**(polyimide) and bonded to the crystal holder with thermally conductive (but electrically insulating) epoxy adhesive. The oscillator and temperature control circuits are mounted on alumina substrates 1/2" X 5/8" X 0.015". These circuits and their method of fabrication will be described in a subsequent section. These substrates are bonded to the heater with the same thermally conductive epoxy adhesive. Thus, only one heater and control circuit are required. The general plan is shown in Fig. 1.

Two critical components, the temperature sensing thermistor and the heater control transistor, are located on top of the HC-6 crystal holder. The thermistor is electrically insulated from the metal holder by a thin film of thermally conductive epoxy. The control transistor chip is attached directly to the holder by soldering with CERROSEAL-35. Short flying leads connect each device into the temperature control circuit.

4. Electrical Leads

In selecting the electrical lead material and its dimensions for dc input power and RF output power, a trade-off must be made between electrical and thermal conductivity. Copper would be an obviously poor choice due to the intolerably high thermal conductivity. Nichrome, on the other hand, has low thermal conductivity but a high electrical resistance—about 65 times greater than copper. Nickel possesses a reasonable balance between good electrical resistance (five times copper) and low thermal conductivity (about 1/6 of copper). We made the electrical leads of 10 mil nickel. The resistance of such wire at 25°C is ~ 0.7 Ω/ft. Small diameter (size 24) teflon tubing is used as insulation for each lead.

5. Thermal Insulation

In order to be within the maximum allowable operating power of 250 mW at any ambient temperature between -40°C and +75°C a very efficient insulation is required around the isothermal region. The major part of the power loss reported for Model No. 1 (Contractor Evaluation Report, this Contract, August 1972) is considered to be down the stainless-steel pedestal which supports the components in the isothermal zone. At -40°C ambient, the conductive heat loss through this stainless-steel pedestal is about 375 mW. For this reason, Models Nos. 2 and 3 use a support pedestal made of polyimide (VESPEL). By way of comparison the calculated heat loss through this type of support, for a -40°C ambient, is about 10 mW.

Once the need for a dewar-type vacuum vessel was eliminated, selecting a suitable insulating material to use inside the single-wall vessel was necessary. At the 250 mW maximum operating power level after a one minute

* Thermofoil Heater, Minco Products, Inc.
** E. I. du Pont de Nemours & Co., Wilmington, Del.
warm-up period, and the worst case situation when the ambient temperature is 
-40°C (ΔT = 125°C) the K value of the thermal insulation must be about
2 x 10^{-5} W cm/cm^2 ΔT. Few materials approach within even one order of this 
value. The plastic foam insulators have K values of 2 x 10^{-4} or more depend-
ing on their density. Two types of "super insulation" are available, i.e., 
Super Insulation (Linde) and NRC-2 (King-Seeley Thermos Co.). Both are 
intended for use in an evacuated enclosure and both function as insulators 
by providing high reflectivity to infrared radiation, coupled with very low 
lateral conductivity. NRC-2 was selected as the best suited for our needs 
since it can be more easily formed into intricate shapes.

NRC-2 is made of 0.00025" mylar film coated on one side with 300 A of 
high purity aluminum. The lateral conductivity of the Al is of course more 
than that of the mylar. When properly installed the K value for NRC-2 is 
about 4.1 x 10^{-7} W cm/cm^2°C, i.e., two orders better than required! To 
obtain the above K value, a pressure of 10^{-4} torr is assumed. Calculations 
indicate that a somewhat higher pressure (as much as two orders) can be 
tolerated with reasonably small degradation of K.

Maintaining < 10^{-2} torr pressure inside the vacuum vessel over a long 
period of time requires vacuum compatible materials to be used and that 
evacuation and baking be properly done at the lowest possible pressure and 
the highest possible temperature.

It was discovered, after the application of NRC-2 to Model No. 1, that 
it introduced capacitive coupling between the oscillator components and 
itselv itself. Thus, any relative movement between the NRC-2 and oscillator 
resulted in frequency changes. To eliminate this problem it was necessary 
to surround the crystal and circuit boards in the isothermal region with a 
100 mesh stainless steel screen. This screen was made 7/8" in diameter by 
1 1/8" long and is supported by four 0.030" stainless-steel wires which are 
attached to the base. The screen and support wires represent a thermal 
 drain of approximately 50 mW at -40°C ambient.

Models Nos. 2 and 3 have the screen secured to the polyimide post 
(see Figs. 8 and 9) just below the crystal and thus eliminates the 50 mW 
heat loss down the support wires in Model No. 1.

In Model No. 1, sixteen layers of NRC-2 insulation are used between the 
screen and the outer wall of the unit. Due to the support wires it was 
difficult to adequately shield the lower part of the isothermal region from 
the base.

Models Nos. 2 and 3 use five layers of NRC-2 insulation. The insula-
tion is wrapped around the polyimide support pedestal to provide shielding 
between the isothermal region and the base. Figure 10 shows Model No. 3 
with NRC-2 installed. This model is shown ready for evacuation and sealing.

B. Electrical Fabrication Details

1. Oscillator Circuit Description

The MOSFET crystal controlled oscillator circuit diagram appears 
in Fig. 11. It consists of an oscillator stage, buffer stage, and fine
Fig. 8. TMXO No. 3 before NRC-2 and cap installed.
Fig. 9. TMX0 No. 3 showing screen installation.
Fig. 10. TMXO No. 3 showing NRC-2 installation.
Fig. 11. Circuit diagram of the MOSFET Crystal-Controlled Oscillator.

\[ R_a, R_b, \text{ and } R_d \text{ selected for final frequency adjustment.} \]
frequency control network. The oscillator is a modified Pierce configuration. The feedback network provides a load capacitance for the crystal of 32 pF. This load capacitance is determined primarily by capacitors C_a, C_b, C_c, and C_d. Capacitor C_d is a chip capacitor which is variable from 1 to 31 pF in 1 pF steps. Coarse tuning is accomplished with this capacitor, which changes the frequency \( \Delta f/f \) approximately \( 2 \times 10^{-7} \) per picofarad change in capacitance. Total tuning range with this capacitor is about 38 Hz.

Fine tuning is done by setting the bias on D_1 so that the frequency is within \( 1 \times 10^{-8} \) of the desired frequency. This bias is adjusted by resistors R_a, R_b, and R_d. The bias supply for D_1 is derived from zener regulator D_2. This zener is a low-level type and operates at currents down to 50 \( \mu \)A without loss of zener action. An input voltage of +9V is supplied from the regulated dc supply.

After coarse adjustment of frequency to within \( \pm 1 \times 10^{-8} \) of 5 MHz, final tuning to \( \pm 1 \times 10^{-10} \) of 5 MHz is accomplished by the frequency adjustment potentiometer R_v. The range and resolution of this control is determined by the ratio \( R_v/R_a + R_b \). It is this ratio which determines the voltage appearing across the potentiometer, as well as the maximum and minimum voltages applied to tuning diode D_1.

The tuning diode D_1 and capacitor C_e are effectively in parallel with C_b as far as AC signals are concerned. With C_e small, the tuning diode voltage range can be made large enough so that small changes in zener voltage of \( \sim 1 \) mV do not affect the frequency stability.

A load capacitance of 32 pF will pull the frequency of the crystal about +875 Hz above the series resonant frequency or approximately 27 Hz/pF. To change the frequency \( \pm 1 \times 10^{-8} \), the load capacitance must change approximately \( \pm 0.002 \) pF, and therefore, C_b, in parallel with the series total of C_e plus D_1 must change by approximately 0.033 pF. The value of C_e is 8.2 pF and that of D_1 is about 80 pF. Their series capacitance is

\[
C_S = \frac{(8.2)(80)}{8.2+80} = 7.437 \text{ pF.}
\]

When D_1 is changed to 85 pF the capacitance, C_S, becomes 7.478 pF and \( \Delta C_S = 7.478 - 7.437 = 0.041 \) pF, which is approaching the desired value of 0.033 pF.

To change D_1 by 5 pF requires a bias voltage change of approximately 0.5 volt. Thus the bias on D_1 must vary \( \pm 0.5 \) volt from the set value in order to tune the oscillator about \( \pm 1 \times 10^{-8} \), as required by the Technical Guidelines. Since the potentiometer has a 25 turn adjustment from end to end, then a single turn should cause a \( \Delta f/f \) of approximately \( 8 \times 10^{-10} \) or \( 1 \times 10^{-10}/45^\circ \) of shaft rotation.

Automatic gain control (AGC) on both the oscillator and buffer stages can be described with the aid of Fig. 12. This figure is an equivalent circuit representation of a dual gate MOSFET(3). The transistor includes three diffused regions connected by two channels, each of which is controlled by its own independent gate. Unit No. 1 acts as a conventional,
Fig. 12. Equivalent circuit representation of the two units in a dual-gate MOSFET.
single-gate MOSFET, with the central diffused region acting as the drain and Unit No. 2 acting as a load resistor. When $I_D$ increases, the source voltage increases in a positive direction and the voltage between the source and gate 2 increases. Thus the bias on gate 2 becomes more negative with respect to the source. When this occurs the resistance $R_2$, of the channel associated with gate 2 increases and reduces the current $I_D$. As $I_D$ decreases the opposite occurs, i.e., gate 2 becomes more positive with respect to the source and the channel resistance ($R_2$) associated with gate 2 decreases. Therefore the drain voltage of Unit 1 is controlled by the channel resistance of Unit 2 and AGC results from this action. Actual signal levels vary less than 5 mV with the value of $V_{DD}$ changing from 8.5 to 9.5 volts.

The buffer stage is a basic common-source configuration with gate 2 grounded to provide AGC and also act as an RF shield between the drain output circuit and the input. This stage does not provide gain with the required load but delivers between 400 to 600 mV peak-peak across 1000 Ω. Other performance data obtained from the breadboard model of this oscillator are: (1) Frequency/Voltage Stability of about $1.2 \times 10^{-11}$/mV change in input voltage and without input regulator or tuning diode, $D_1$; (2) Frequency/Load Stability of less than $1 \times 10^{-11}$ for ±10% change in load; (3) input power to oscillator is 10 mW maximum and (4) crystal dissipation is between 3 and 10 μW depending upon the $R_S$ value of the crystal.

2. Temperature Control Circuit Description

A very stable temperature is required by a crystal oven which is part of a reference oscillator. When the quartz resonator is designed for fast warm-up by the inclusion of helium within the holder, the problems are magnified due to the extreme temperature sensitivity of the resonator.

Figure 13 is the schematic diagram of the proportional temperature control circuit developed for the miniature crystal reference oscillator. It consists of a bridge sensing network, a bridge buffer amplifier (OP-1), a drive amplifier (OP-2), and power control circuit ($Q_1$, $Q_2$ and $R_H$). The operational amplifiers are Fairchild type μA776 and were specifically chosen for their extremely low power consumption, which is in the microwatt range.

The initial circuit utilized a thermistor for the input resistor ($R_T2$) to amplifier OP-2. This was an attempt to minimize temperature overshoot by increasing the gain as the temperature approached the final operating temperature. This approach did not prove to be workable because the operating temperature was sensitive to small gain variations caused by $R_T2$, which resulted in short-term temperature variations of sufficient magnitude to generate frequency instabilities of $\pm 1 \times 10^{-7}$. The thermistor was replaced with a fixed resistor of 1000 Ω.

The control circuitry operates from the regulated +9V supply while the power circuitry operates from the unregulated +12V input. The operational-amplifiers are intended to be used with positive and negative supply voltages. In order to use them with only a positive supply voltage, a zener diode ($D_1$) establishes a common point for the circuit and therefore the ground terminal becomes −4.5 V with respect to circuit common. The positive input to the circuit (+9 V) then becomes +4.5 V with respect to circuit common.
Zener diode D2 (4.5 V) prevents the output of OP-2 from driving Q1 when the bridge is near balance. At bridge balance the output from OP-2 is near \(+4.5\) V due to the method of obtaining the \(\pm4.5\) V described above. When the bridge becomes unbalanced, the output from OP-2 increases and D2 conducts, applying drive to Q1.

Transistors Q1 and Q2 are connected in a Darlington configuration and provide a gain of approximately 30. Transistor Q2 is mounted on top of the crystal holder as described previously. After the initial warm-up period, Q2 becomes the major source of heat dissipation. Because of the low power requirements the dissipation cannot be wasted and therefore is used to supply heat to the crystal holder.

The final temperature adjustment to set the temperature precisely at the UTP of the crystal must be done before final tuning of the oscillator. This is accomplished in the following manner. The frequency of the crystal at its UTP is accurately measured by using a synthesizer driven crystal bridge. The crystal heater during this measurement is controlled by an external dc supply so that the temperature of the crystal increases very slowly through its UTP. The frequency will be continuously monitored so that the UTP frequency is easily recognized. The proportional control circuit is next connected to the heater. The operating temperature is now set so that the crystal frequency is the same as above. Adjustment of R4a and R4b (see Fig. 13) sets this temperature. Resistor R4b is a Motorola type MMCR-100-025 or MMCR-100-100. These chip resistors can be varied in 25 \(\Omega\) or 100 \(\Omega\) steps respectively by bonding to their various pads. After the operating temperature has thus been adjusted, the crystal is connected to the oscillator circuit and the oscillator tuned as previously described.

3. Voltage Regulator

A voltage regulator is used to provide the operating voltage for the oscillator and temperature control circuits. The regulator is located outside of the isothermal region, because of thermal mass limitations.

Figure 14 is the schematic diagram of the voltage regulator circuit. It provides +9 V to the oscillator, oscillator tuning network, and the temperature control circuit, with a typical line regulation for an input of 12 V \(\pm\) 5% of 0.01% of the output voltage.

The input power to the regulator is about 30 mW with a 1 mA load current, with the regulator requiring about 20 mW of this power. The 30 mW load is the total power requirement for all electronic circuitry, excluding the crystal heater.

In constructing the complete voltage regulation unit all the external components were soldered directly to the Fairchild type \(\mu\)A723 regulator. The resistors are one-eighth watt size and are placed on the base of the TO-5 regulator holder while the 100 pF capacitor is attached to the side of the regulator. After soldering all connections, the components were potted to the TO-5 base with silicon rubber. Only the input, output, and ground leads are carried through the potting. This sub-assembly is attached to the base of the main unit.
Fig. 13. Schematic diagram of temperature control circuit.

OP-1, OP-2: μA776
D1, D2: MZC4.7B1 MOTOROLA
RT1: VECO THINISTOR TYPE FN1A6
R4: TRIM TO SET TEMPERATURE
Q1: MOTOROLA UNENCAPSULATED
     TRANSISTOR MMCS2222
Q2: MOTOROLA UNENCAPSULATED
     TRANSISTOR MJCO82
At 12 V input and load current of 1 mA
the power input is 30 mW.

R₁ : 1.5kΩ/1/8 W
R₂ : 6.8kΩ/1/8 W
R₃ : 1.5kΩ/1/8 W
C₁ : 100 pF
Vᵢn : 12 V ± 5%

Fig. 14. Schematic diagram of voltage regulator circuit.
4. **Microcircuit Fabrication**

High purity alumina was selected as the substrate material and was used in the as-fired conditions; i.e., the surfaces were not mechanically polished. Film conductors are gold over chromium.

Figures 15 and 16 are photographs of the hybrid oscillator and temperature control circuits. Resistors are of the flip chip variety with solder terminations, as are also the capacitors, except where previously noted.

The initial attempts at fabricating these circuits used solder reflow to attach the resistors and capacitors, which is why these components were obtained with solder terminations. This type of attachment was found to be incompatible with the pure gold conductor material on the substrates due to undesirable leeching of the gold film by the solder. This leeching of the gold resulted in very poor electrical bonds as well as poor adherence of the chip to the substrate. This problem left us with two possible solutions - one, to change the substrate conductor material to one which would be less prone to leeching or, second, to change the method of attaching the components to the gold substrate conductors.

Because of the necessity of gold substrate conductors in wire-bonding it was decided to retain the gold substrate conductors and to attach the solder terminated components with conductive epoxy. At first this seemed to be an acceptable method of attachment but later experience proved it to be a mistake. Section IV-A discusses this in greater detail.

Electrical connection to the active devices is by thermocompression bonded gold wires. Both wedge-bonding and ball-bonding are used. Many problems were encountered during fabrication of the microcircuits but by far the largest was the unreliability of the wire bonding. This problem is also discussed in Section IV-A.

C. **Resonators**

Commercially available 5 MHz crystal units in HC-6 cold-weld holders were used in the three TMXO prototypes. The only special feature of these resonators is the inclusion of helium, after evacuation and bakeout, to a pressure of 50 torr. Complete specifications are given in report TR ECOM-0301-1 (semiannual). The use of helium-filled resonator holders for fast thermal response was described by Hicklin and Bennett(4).

Figure 17 shows the TCF of one unit but is representative of all of them. The UTP is slightly higher than desired but has not been noticeably effectual upon the warm-up time.

Figure 18 shows the aging over a two-week period of the five units purchased. None of the units reached the specified aging rate set forth in the Technical Guidelines.

Retrace has been observed in the completed TMXO models and is attributed to the resonators.
Fig. 15. Photograph of hybrid oscillator board.
Fig. 16. Photograph of hybrid temperature circuit board.
Fig. 17. Temperature coefficient of frequency of unit 6.
Fig. 18. Aging data for 5 MHz resonators purchased for the tactical miniature crystal oscillator.
III. EXPERIMENTAL TEST METHODS

A. Introduction

The nature of the tests performed was to simulate actual operating conditions such as variations in the ambient temperature and then to measure the pertinent characteristics of the device such as warm-up time, operating power, frequency, stability, etc. The required measurements can be roughly grouped into two classifications; electrical and physical. The electrical measurements include those of voltage, current and frequency; physical measurements were those of time, temperature and vibration.

B. Frequency Measurement

The two analytical systems used to measure frequency are shown in Figs. 19 and 20 respectively. Figure 19 shows the output signal of the TMXO being compared with the in-house standard signal Manson Model RD180A oscillator. These two signals are used as input and external standard for Hewlett-Packard Model R360A computing counter. The in-house secondary standard frequency from the Manson oscillator is calibrated by comparison with the Eastern Loran-C chain of stations. The Loran-C signal is received in a Beukers Model 112 frequency reference unit. This instrument uses the transmitted signal to synchronize the quartz crystal oscillator. The output of this oscillator is then compared with the Manson oscillator output and the difference indicated on a direct reading meter and recorded on a strip-chart recorder. The 1 MHz signal from the Manson oscillator is converted to a 5 MHz signal by means of a Hewlett-Packard Model 5100A/5110A frequency synthesizer.

The Hewlett-Packard computing counter was borrowed from the Electronics Division of the Engineering Experiment Station. The system shown in Fig. 19 was used mainly for short-term measurements, i.e., 1 second to 60 minutes. The other system shown in Fig. 20 was used for longer measuring periods such as overnight. The data from this system are plotted on a model CR-1 cosine phase plotter which is manufactured by RMS Engineering Incorporated, Atlanta, Georgia. The special feature of this plotter is that it compares standard frequency from 10 KHz to 5 MHz and provides a resolution of 1 part in $10^{11}$ in one hour or less.

The waveform of the output signal of the TMXO and the RF output voltage were measured with a Tektronix type 545 oscilloscope. A type H wideband calibrated amplifier was used with this Tektronix oscilloscope. Its minimum sensitivity is 5 mV per cm dc coupled and has a rise time of approximately 0.020 μ sec.

C. Power Requirements

The operating power during this test was supplied by a Model CK40-0.8M by KEPCO Power Supply. The manufacturer's specifications for this supply are as follows: line regulation, less than 0.01% output change per 115 V ± 10 V operation; load, less than 0.01% for no load to full load; stability, less than 0.01% over an 8 hour period after warm-up; ripple, less than 0.5 mV rms.
Fig. 19. System for the measurement of warmup time, warmup power and the frequency during and after warmup. Frequency readout is digital.
Fig. 20. Alternate system for making performance measurements. The frequency readout is analog. This method especially suited for long periods of operation with equipment unattended.
The current flowing from this power supply to the TMXO unit was monitored by triplet Model 630-A multimeter. The stated accuracy of this meter is 1 1/2% of full scale for all dc ranges. The power input was not measured directly in watts but computed from the current and voltage readings.

D. Temperature Simulation

Simulation of ambient temperature of -40°C to +75°C was effected by using temperature control baths of suitable liquids. For the -40°C ambient temperature a mixture of alcohol and dry ice was used. This liquid was contained in a large mouth glass jar. Once the temperature -40°C was attained by the liquid the temperature could be maintained quite accurately by the occasional addition of a few pieces of dry ice.

A high ambient temperature (+75°C) was obtained by submerging the TMXO in a magnetically stirred bath of vacuum pump oil. Heat was applied directly to the oil by copper-encased heaters and the temperature controlled by mercury thermostat. The temperature control with respect to the stated temperature was better than 0.1°C.

E. Vibration Testing

The shock and vibration test equipment was comprised of a MB electronic vibromatic system* using two type 2120 MB amplifiers and an EA 1500 exciter. The amplifiers are driven by Hewlett-Packard Model 202C audio oscillator. A strobe light (General Radio Strobotac #631B) and a Tektronix type 532-S7 oscilloscope completes the system. The manufacturer's performance data of MB Model EA1500 is as follows: force output, 0-50 lbs vector; displacement, dynamic=0.5 inch D.A; frequency range 5 Hz to 10 KHz; maximum acceleration, 124 g.

* MB Electronics, Division of Textron Electronics Incorporated, New Haven, Connecticut.
IV. EXPERIMENTAL RESULTS

A. TMXO Model No. 1

1. Temperature Calibration

The procedure for setting the operating temperature was described in Section II-B-2. Using this procedure it was determined that a total resistance for $R_4 (R_{4a} + R_{4b})$ of around 34.5 kΩ was needed. Before these actual chip components were bonded into the circuit an experiment was performed, using a resistance decade box for $R_4$, to check the variance of the warm-up characteristics due to small changes in the operating temperature. Three warm-up runs were made, one each with the operating temperature below and above the exact UTP temperature and one very slightly below the UTP temperature. Figure 21 shows the results of this experiment. With $R_4$ set to 36.7 kΩ, the final operating temperature is just below the UTP temperature of the crystal. When $R_4$ is set to 34.0 kΩ the operating temperature is just above the UTP temperature of the crystal. From these two curves it was determined that somewhere between the values of 36.7 kΩ and 34.0 kΩ for $R_4$, the warm-up could be optimized. The difference in these first two warm-up runs is due to the temperature overshoot during warm-up and where the final operating point falls on the TCF curve of the crystal. The third warm-up run was made with $R_4$ set to 35.4 kΩ, which set the final operating temperature to just slightly below the exact UTP temperature of the crystal. The exact UTP temperature is reached when $R_4$ is equal to 34.5 kΩ.

On the basis of the data presented in Fig. 21, a value of 35.4 kΩ was chosen as the optimum value for $R_4$. To produce this value in the hybrid circuit requires that $R_{4a}$ plus $R_{4b}$ add to equal 35.4 kΩ. Resistor $R_{4a}$, a flip-chip, was selected by measuring a number of 33.0 kΩ chips at approximately 90 °C and choosing one which would leave a difference, when subtracted from 35.4 kΩ, that would be a multiple of 25. Then resistor $R_{4b}$, a Motorola MMCR-100-025, could be bonded at the appropriate bonding pads to provide the necessary total resistance of 35.4 kΩ. The actual value of $R_{4a}$ selected was 33.47 kΩ. The bonding pads used on $R_{4b}$ set its value at 1.85 kΩ. The total resistance of this combination is then 35.32 kΩ. Figure 22 shows the warm-up data for TMXO Model No. 1 after $R_{4a}$ and $R_{4b}$ were connected to set the final operating temperature. In this figure, as in all the warm-up curves in this report, the reference frequency was taken at the last time shown unless otherwise indicated.

Since the input current variation during warm-up indicates that thermal equilibrium is achieved in about 15 minutes then a reference frequency taken at 15 or 20 minutes should result in offset calculations which fairly depict the warm-up characteristics. Thus, from Fig. 22 the following warm-up specifications are: after one minute the frequency offset is less than $\pm 2 \times 10^{-9}$ (resolution of measurement is $\pm 2 \times 10^{-9}$), after two minutes the offset is $-4.2 \times 10^{-8}$, after four minutes the offset is $-2 \times 10^{-9}$, and after fifteen minutes the offset is still $2 \times 10^{-9}$. Note that this warm-up was conducted
Fig. 21. Effect of temperature calibration on warm-up characteristics.
TMXO-1 in air.
Fig. 22. TMXO-1 warm-up after temperature calibration. Oscillator circuit not attached to crystal. In air.
in air at 25°C ambient and that the crystal was not connected to the oscillator circuit. The temperature circuit is in its final form and permanently attached to the side of the crystal holder. The offsets listed above fall within the desired warm-up goals listed in the Technical Guidelines except the 15 minute offset which is $+1 \times 10^{-9}$ higher than desired.

2. Frequency Calibration

After the operating temperature was established the crystal was connected to the oscillator circuit. Power was applied and sufficient time allowed for temperature stabilization before an output frequency of 5000032 Hz was accepted and recorded. Capacitor $C_d$ was then bonded into the circuit, as previously described, to lower the frequency to 5000000.2 Hz. Closer calibration was accomplished with resistors $R_a$ and $R_b$ and the frequency was 5000000.0 after the final calibration. Range of adjustment of $R_v$ was $2.8 \times 10^{-7}$ end-to-end.

At this point a couple of layers of NRC-2 were wrapped around the intended isothermal region to check its effect on the frequency. It was found that not only does the NRC-2 lower the output frequency but also makes the output very sensitive to movements of the NRC-2. The NRC-2 evidently introduces undesirable coupling between the more sensitive components ($C_a$, $C_b$, $C_c$, $C_d$) of the oscillator circuit and thus changes the effective load capacitance. It was for this reason that we decided to investigate CAB-O-SIL* as an alternate insulating material. CAB-O-SIL is a fumed silica powder with a reported $K$ value of $2.2 \times 10^{-5}$W/cm/cm$^2$°C. After the initial attempt to seal this model failed, described further in Section IV-A-4, the use of CAB-O-SIL was rejected since it was found to "settle" during out investigation into the sealing failure. The capacitive coupling problem with the NRC-2 was then solved by using a screen, around the crystal and circuitry, to keep the NRC-2 far enough away to eliminate its coupling effect. The dimensions and thermal losses attributed to this screen were discussed in Section II-A-5. The installation of this screen does not affect the frequency calibration.

3. Initial Warm-up Performance (Pre-Seal)

In Section IV-A-1 and Fig. 22 the warm-up capabilities of Model No. 1 in air were discussed. After the frequency calibration was accomplished another warm-up test was conducted. This test was performed in air at 25°C ambient and without NRC-2 installed. Figure 23 shows the results of this test and for purposes of comparison, the warm-up results of Model No. 1 after evacuation. The "in-air" results obtained and depicted in Fig. 23 are quite different from the initial warm-up data shown in Fig. 22. Since the data represented by Fig. 22 did not include any possible effects on warm-up contributed by the oscillator circuit it was conjectured that the degradation in warm-up performance, when the oscillator was used, was due to the time involved for the load capacitors in the oscillator to reach equilibrium temperature. Later data contradict this hypothesis and it is now believed that problems in the temperature control circuit of this unit were beginning to become evident.

* Cabot Corporation, Boston, Massachusetts.
Fig. 23. TMXO-1 warm-up comparison at +25°C ambient before and after encapsulation.
4. Performance and Evaluation Tests

a. Introduction. As previously stated, Model No. 1 failed to seal on the initial attempt by cold-welding and a discussion with the Contracting Officer's Technical Representative (COTR) resulted in a base material modification. This in turn required that evacuation of the unit be done through a copper pumpout tube. Permission was received from the COTR to carry out the evaluation test with the TMXO being continuously pumped with an eight liter per second Vactron pump. The base pressure during the following tests was $5 \times 10^{-8}$ torr.

The relevant technical data and goals for the exploratory development TMXO models were included in the contract as Technical Guidelines. In order to maintain a direct association with these guidelines, the results of the various evaluations will be given in the same order as set in the guidelines.

b. Volume. The volume of the extended type-D holder enclosing the TMXO is 4.8 in$^3$. Adding the pinch-off tubulation increases the volume to 4.9 in$^3$.

c. Operating Voltage. All tests except where specified otherwise were performed at a nominal input voltage of $\pm 12$ V dc.

d. Warm-up Power. An input power of 7.8 W (set by the heater resistance and $Q_2$ saturation resistance) was applied during warm-up for 70 sec at $-40^\circ$C, 30 sec at $24^\circ$C, and 10 sec at $75^\circ$C. These values represent input energy requirements of 546, 234, and 78 joules respectively. The warm-up power goal specified in the Technical Guidelines is 10 watts at any ambient; the maximum allowable time that 10 watts is available is 60 seconds. This would represent a maximum energy availability of 600 joules during the first 60 seconds following turn-on.

The electrical energy required over a 15 minute period starting at turn-on is shown in Fig. 24. The maximum available energy over the first 15 minute period, calculated from Technical Guidelines power requirements, is 810 joules. The actual energy required as shown in Fig. 24 is 1168, 837, and 385 joules for ambient temperatures of $-40^\circ$C, $+24^\circ$C, and $+75^\circ$C respectively. When looked at in this manner the power consumption does not fall too far short of the goals.

e. Operating Power. The operating power levels for Model No. 1 in ambient temperatures of $-40^\circ$C, $+24^\circ$C, and $+75^\circ$C, as shown in Fig. 25, are 625 mW, 316 mW, and 115 mW respectively. Figure 25 also shows the total power input to the TMXO for the first 16 minutes, for each of the three test temperatures. The 250 mW goal is met when the TMXO is operating at ambients of approximately 50°C and above.

f. Power Aging. This feature was not measured because the evaluation tests for this model were conducted while under continuous evacuation.

g. Frequency Adjustment. The measured adjustment range is $\pm 1.5 \times 10^{-7}$. The 25-turn potentiometer gives a resolution of $6 \times 10^{-9}$/turn and is adjustable to $\pm 1 \times 10^{-10}$ of the final frequency. The range of $1.5 \times 10^{-7}$ was needed, in lieu of the $1 \times 10^{-8}$ requested, because of
Power requirements first 15 min

at -40°C: 1168 J
+24°C: 837 J
+75°C: 385 J

Fig. 24. Warm-up power profiles for first 15 minutes after turn-on. The technical guidelines requirement is 810 W-sec over the entire ambient temperature range.
Fig. 25. Total operating power vs time for operating TMXO Model No. 1 in different ambient temperatures.
two reasons. Firstly, the wider tuning range made frequency calibration an
easier task and secondly, the degree of aging and retrace of the commercial
resonators used in these TMXO models made the $\pm 1 \times 10^{-8}$ tuning range appear
impractical.

h. Frequency/Temperature Stability. These data were obtained by
operating the TMXO at -40°C for 60 minutes and then recording its frequency,
and then operating it at +75°C for 60 minutes and remeasuring the frequency.

\[
F_{-40} = 5000000.323 \text{ Hz}
\]
\[
F_{+75} = 5000004.016 \text{ Hz}
\]
\[
\Delta F/F = +7.4 \times 10^{-7}
\]

i. Frequency/Load Stability. The reference frequency was measured
with a load impedance of 1000 |0° Ω. For a plus and minus 10% change in
resistive loading the \(\Delta F/F\) was 1 \times 10^{-9}. For a plus and minus change in the
load phase angle of 20° the \(\Delta F/F\) was 2.2 \times 10^{-9}. A capacitive loading change
induces the largest \(\Delta F/F\), -1.6 \times 10^{-9} for \(Z_L = 1000|20° \Omega\).

j. Frequency/Voltage Stability. The recorded frequency change for
an input voltage variation from 11.4 to 12.6 V dc was -1.4 \times 10^{-9}.

k. Frequency Aging. The aging goal of $\pm 2 \times 10^{-10}/$week after a
30 day stabilization period appears to be beyond the state-of-the-art with
commercially available, aluminum plated crystals designed for fast warm-up
applications. No time was available to obtain an aging rate.

l. Short Term Stability. The short term frequency stability is
approximately 4 \times 10^{-18} for a 10 sec sampling time. Additional sampling
times were not undertaken because it was obvious that this goal was not met.

The failure to meet this goal is not due to any major design faults in
oscillator design. It is attributed to poor microcircuit fabrication tech-
niques which cause instabilities not only in the oscillator circuit but also
in the temperature control circuit. The latter circuit instabilities result
in small temperature perturbations, which are sensed by the extremely fast
thermal response of the resonator, and reflected as frequency perturbations.

m. Warm-up Time. Before the frequency vs warm-up data were
recorded at each ambient temperature the TMXO was allowed to equilibrate
in the -40°C ambient for 45 minutes and in the +75°C ambient for 30 minutes
before power was applied. The measured warm-up data for each of the three
ambient temperatures are depicted in Fig. 26.
Fig. 26. TMX0-1 warm-up after encapsulation and evacuation to <1x10^-5 torr.
At -40 °C  

\[ \Delta F/F \text{ at 1 min after turn-on} = +1.5 \times 10^{-6} \]
\[ -1.2 \times 10^{-6} \]
\[ -9.96 \times 10^{-7} \]

\[ \Delta F/F \text{ at 2 min after turn-on} = -4.7 \times 10^{-7} \]
\[ -8.4 \times 10^{-7} \]
\[ -4.83 \times 10^{-7} \]

\[ \Delta F/F \text{ at 4 min after turn-on} = -2.1 \times 10^{-7} \]
\[ -3.5 \times 10^{-7} \]
\[ -1.63 \times 10^{-7} \]

\[ \Delta F/F \text{ at 15 min after turn-on} = -2.4 \times 10^{-8} \]
\[ -5.2 \times 10^{-8} \]
\[ -1.88 \times 10^{-8} \]

It is now thought that the temperature control circuit of this model was not performing properly during these tests and was functioning at very low system gain.

Figure 27 is a comparison of the warm-up at 25°C between the pre-seal (but evacuated) condition and sealed-off condition. The warm-up after seal was performed roughly two weeks after the copper tubulation was pinched off. The input power required after the warm-up indicates this unit is now at atmospheric pressure, due either to an insufficient seal or internal out-gassing.

n. Frequency Recovery at -40°C Ambient. The output of Model No. 1 after warm-up during each turn-on period was determined over a three cycle test. Each cycle consisted of operating the unit for 60 minutes, then recording the frequency, and then letting the unit sit at the -40°C ambient for a further 60 minute period with the power off. The frequencies recorded after each turn-on are:

Run No. 1: \( F = 5000000.300 \text{ Hz} \)
Run No. 2: \( F = 5000000.339 \text{ Hz} \)
Run No. 3: \( F = 5000000.302 \text{ Hz} \)

The maximum frequency deviation was \( 7.8 \times 10^{-9} \).

o. Output Voltage. The output voltage was measured at 177 mV rms across a load of 1000Ω.

p. Shock and Vibration. Since this model was tested while still attached to the small Vaclon pump it was not possible to subject it to the shock and vibration test as specified in Test Method 213A, Test Condition J, MILL-STD-202D. However, individual elements were tested. The results showed that the mechanical resonances of the pedestal assembly were above 55 Hz. The peak-to-peak amplitude of the testing machine was 0.060 inches.

B. TMXO Models Nos. 2 and 3

1. Temperature Calibration
Before final seal but evacuated to <1x10^{-5} torr

Fig. 27. TMX0-1 warm-up before and after final sealing.

Two weeks after final seal

Before final seal but evacuated to <1x10^{-5} torr
The unreliable operation of the hybrid temperature control circuits of Models Nos. 2 and 3 have made accurate calibration a difficult accomplishment. Model No. 2 has undergone temperature calibration on two occasions due to control circuit failure after the first attempt. The resistance \( R_4 \) needed initially for proper temperature adjustment was 26.5 k\( \Omega \). The second adjustment required an \( R_4 \) of 57.0 k\( \Omega \). No actual components were replaced between the two calibrations but many of the resistors were removed and then replaced with a different conductive epoxy. The problem with the circuit was attributed to an unreliable conductive epoxy bond to one of the resistors. Model No. 3 has also undergone two calibration attempts. During the first attempt the control circuit lost control and overheating began. The problem was found to be defective bonding to control transistor \( Q_2 \). This component was replaced and calibration resumed. A resistance for \( R_4 \) of 31.0 k\( \Omega \) was required.

The problem of thermal runaway experienced by both Models 2 and 3 are discussed in detail in Section V-B.

2. Frequency Calibration

Frequency calibration of these two models was accomplished in the same manner as Model No. 1. Because of the control circuit problems the frequency calibration became a problem at times. Also the hybrid oscillator circuits developed bonding problems. These are associated with the conductive epoxy used for attaching the resistors and capacitors.

3. Initial Warm-up Performance

During evaluation of the warm-up for Model No. 1 it was observed that the warm-up performance was degraded considerably after the crystal was connected to the hybrid oscillator (See Section IV-A-3 and Fig. 23). At the time it was thought that this was due to a longer temperature stabilization time for the load capacitors and other oscillator components, than for the crystal. To investigate this hypothesis, warm-up data was acquired on Model No. 2 with and without the crystal connected to the hybrid oscillator. Both warm-up runs were made in air at 25°C ambient. Figure 28 depicts the results of this experiment. As seen from this figure, very little difference exists between the two warm-ups, which is really the expected result. The small difference seen after 3 minutes is probably due to the slightly longer thermal stabilization time required by the oscillator components.

4. Performance and Evaluation Tests

a. Introduction. The evaluation tests for Models Nos. 2 and 3 were conducted in a similar manner to Model No. 1 except these latter models were in a packaged and sealed condition during the test. No evacuation was performed during the testing.

Model No. 2 was evacuated, baked out at 100°C for about 24 hours and sealed, as previously described, at a pressure of \( 3 \times 10^{-6} \) torr. No leaks were detected initially. During later testing it became evident from power requirements, that the internal pressure had increased to greater than \( 10^{-2} \) torr. This pressure rise is due, most likely, to outgassing, which was observed to be quite appreciable during the evacuation and bakeout just prior to sealing.
Fig. 28. TMXO-2 warm-up showing effect of oscillator circuitry.
Model No. 3 was sealed in air because thermal runaway occurred in a low pressure environment.

Neither unit would operate reliably at the +75°C ambient test temperature due again to the thermal runaway characteristics which these units developed.

The performance data is listed in the same manner as Model No. 1 with the data for Model No. 2 documented first, then followed by the data representing Model No. 3.

b. Volume. The volume of both Models Nos. 2 and 3, which incorporate a two-piece stainless-steel cap in lieu of the modified type-D cap, are approximately 4.5 in³.

c. Operating Voltage. All tests except where specified otherwise were performed at a nominal input voltage of +12 V dc.

d. Warm-up Power. An input power of about 7.2 W was applied during warm-up for approximately 70 sec at -40°C and 27 to 29 sec at 25°C ambients. Figures 29 and 30 show the power requirements up to 60 minutes after turn-on. The discussion of electrical energy requirements during warm-up for TMXO No. 1 (Section IV-A-4d) also is applicable to Models Nos. 2 and 3.

e. Operating Power. Figures 29 and 30 show the operating power requirements of Models Nos. 2 and 3. Model No. 2 was evacuated before sealing but outgassing within the holder increased the internal pressure to > 10⁻² torr, although the slightly lower operating power requirements of Model No. 2 indicate the internal pressure is lower than one atmosphere. From Fig. 29, operating power at -40°C is about 1.2 W and at +25°C is 678 mW.

Model No. 3 was not evacuated and this is reflected directly by the power consumption. At -40°C the operating power is about 1.3 W. The reason the power does not stabilize during the -40°C operation (See Figs. 29 and 30) is due to the slight heating of the -40°C liquid bath, used for testing, by the TMXO. At +25°C the operating power decreases to 756 mW.

f. Power Aging. These data could not be obtained due to the poor thermal properties of the TMXO package.

g. Frequency Adjustment.

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Highest Frequency</th>
<th>Lowest Frequency</th>
<th>ΔF/F</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4999998.565</td>
<td>4999997.423</td>
<td>2.28 X 10⁻⁷</td>
</tr>
<tr>
<td>3</td>
<td>4999999.439</td>
<td>4999998.663</td>
<td>1.55 X 10⁻⁷</td>
</tr>
</tbody>
</table>

Neither unit could be set to 5000000.000 MHz after final sealing. This is probably due to either an operating temperature change or bonding (epoxy) problems in the load capacitance network of the oscillators. Both problems are associated with the hybrid circuit fabrication techniques.
Fig. 29. TMXO-2 input power requirements.

At -40 °C ambient

At +25 °C ambient
Fig. 30. TMXO-3 input power requirements.
h. Frequency/Temperature Stability. Frequency/temperature measurements could not be conducted over the desired temperature range of -40°C to +75°C because of the inability of Models Nos. 2 and 3 to operate at the higher ambient.

An attempt was made with Model No. 2 to obtain these data. The frequency was measured at -40°C and then placed into a 75°C ambient environment. The frequency was recorded at intervals up to an accumulated time of 15 min, at which point the unit ceased to operate properly. The results are given below:

\[
F(-40°C) = 4999999.488 \text{ Hz}
\]

<table>
<thead>
<tr>
<th>Time at +75°C (min)</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4999996.62</td>
</tr>
<tr>
<td>4</td>
<td>4999996.48</td>
</tr>
<tr>
<td>6</td>
<td>4999996.53</td>
</tr>
<tr>
<td>10</td>
<td>4999996.67</td>
</tr>
<tr>
<td>15</td>
<td>4999996.67</td>
</tr>
</tbody>
</table>

The frequency change after 15 minutes at +75°C is \(-5.64 \times 10^{-7}\). The frequency of Model No. 3 was measured after 60 min at -40°C and at +25°C to obtain a TCF over this limited range of \(-7.8 \times 10^{-8}\).

It is speculated that at least some of the frequency deviation is caused by changes in the regulated voltage (TCV), while it is also suspected that water vapor and other condensable gases may be involved in changing the frequency at the -40°C ambient. This would happen if water vapor condensed on the oscillator board and changed its effective load capacitance. Even a change in load capacitance of less than 0.01 pF can adversely affect the frequency. It was never intended to have water vapor present in the TMXO enclosure, but due to the very limited bakeout temperature of Model No. 2 and no bakeout or evacuation prior to sealing of Model No. 3, it is an unavoidable contaminant.

i. Frequency/Load Stability.

Model No. 2

<table>
<thead>
<tr>
<th>Load (Ω)</th>
<th>Frequency (Hz)</th>
<th>ΔF/F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>4999997.818</td>
<td>Reference</td>
</tr>
<tr>
<td>1100</td>
<td>4999997.773</td>
<td>(-9.0 \times 10^{-9})</td>
</tr>
<tr>
<td>900</td>
<td>4999997.928</td>
<td>(+2.2 \times 10^{-8})</td>
</tr>
<tr>
<td>1000</td>
<td>4999997.046</td>
<td>(+4.6 \times 10^{-8})</td>
</tr>
<tr>
<td>1000</td>
<td>4999997.383</td>
<td>(+3.8 \times 10^{-8})</td>
</tr>
</tbody>
</table>

Note: Short-term frequency instabilities are large enough to bias above data.
Model No. 3

<table>
<thead>
<tr>
<th>Load (Ω)</th>
<th>Frequency (Hz)</th>
<th>ΔF/F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>4999999.357</td>
<td>Reference</td>
</tr>
<tr>
<td>1100</td>
<td>4999999.357</td>
<td>&lt;± 2 X 10⁻¹⁰ (Resolution of measurement)</td>
</tr>
<tr>
<td>900</td>
<td>4999999.357</td>
<td>&lt;± 2 X 10⁻¹⁰</td>
</tr>
<tr>
<td>1000</td>
<td>4999999.357</td>
<td>&lt;± 2 X 10⁻¹⁰</td>
</tr>
<tr>
<td>1000</td>
<td>4999999.358</td>
<td>+ 2 X 10⁻¹⁰</td>
</tr>
</tbody>
</table>

The performance of Model No. 3 concerning this parameter is indicative of what this oscillator design is capable of when fabrication techniques are perfected.

j. Frequency/Voltage

<table>
<thead>
<tr>
<th>Model No.</th>
<th>11.4 V</th>
<th>12.6 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>+ 1.4 X 10⁻⁹</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>+ 9.2 X 10⁻⁹</td>
<td>- 6.4 X 10⁻⁹</td>
</tr>
</tbody>
</table>

The reference frequency was taken at 12.0 volts.

k. Frequency Aging. The aging goal of ± 2 X 10⁻¹⁰/week after a 30 day stabilization period appears to be beyond the state-of-the-art with commercially available, aluminum plated crystals designed for fast warm-up applications. No time was available to obtain an aging rate.

l. Short-Term Stability. This goal was not met with any of the three prototype models. The short-term frequency stability of Model No. 2 is particularly poor and this is due primarily to erratic behavior of the temperature control circuit. The short-term frequency stability of Model No. 3 appeared to be slightly better than Model No. 1 (~ 4 X 10⁻¹⁰/10 sec) but was not accurately measured due to the unavailability of the necessary equipment at the time of testing.

It is felt that this parameter can be improved, to the extent that it at least approaches closely the goal of ± 1 X 10⁻¹¹, by improved microcircuit fabrication and if needed, improved voltage regulation for the fine tuning network.

m. Warm-up Time. Only the warm-up characteristics at -40°C and +25°C ambient could be obtained for Models Nos. 2 and 3. Figures 31 and 32
At -40 °C ambient

At +25 °C ambient

Fig. 31. TMXO-2 warm-up after encapsulation.
Fig. 32. TMXO-3 warm-up after encapsulation.
depict the frequency offsets up to 60 minutes after turn-on. It has been shown that the "warm-up" is generally completed after about 15 minutes, but frequency changes due to retrace and aging (related phenomena) are still occurring at the end of 60 minutes. Note in Figs. 31 and 32 that around 25 and 40 minutes, respectively, after turn-on, the frequency drift recorded at the -40°C ambient temperature changes direction. This is probably due to the orientation of the TMXO during testing, which was upside down, and because both units were found to be very prone to convection currents in the surrounding air during warm-up.

Since the regulator was above the heated crystal unit during these tests, it probably received heat by convection from the isothermal region, and its ambient temperature was increased from the -40°C at turn-on. The regulator output voltage began changing enough to affect the tuning diode voltage.

The frequency offsets at the end of 1, 2, 4, and 15 minutes are tabulated below.

<table>
<thead>
<tr>
<th>Time</th>
<th>Model No. 2</th>
<th>Model No. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-40°C</td>
<td>+25°C</td>
</tr>
<tr>
<td>1 min</td>
<td>+4.0 X 10^{-8}</td>
<td>+2.4 X 10^{-7}</td>
</tr>
<tr>
<td>2 min</td>
<td>+7.5 X 10^{-7}</td>
<td>-1.3 X 10^{-7}</td>
</tr>
<tr>
<td>4 min</td>
<td>+4.2 X 10^{-8}</td>
<td>-1.4 X 10^{-7}</td>
</tr>
<tr>
<td>15 min</td>
<td>+9.8 X 10^{-9}</td>
<td>-5.4 X 10^{-8}</td>
</tr>
</tbody>
</table>

n. Frequency Recovery at -40°C Ambient. Model No. 2 incurred a frequency offset of -4.2 X 10^{-8} between successive turn-on periods of 60 minutes. The restabilization time (at -40°C) between turn-on periods was also 60 minutes.

Data on Model No. 3 were insufficient to calculate the frequency recovery, since only one warm-up from -40°C was conducted.

o. Output Voltage. The output of Model No. 2 was measured at 177 mV rms while that of Model No. 3 was measured at 140 mV rms, across a load of 1000Ω.

p. Shock and Vibration. Shock and vibration tests were not performed on either Model No. 2 or Model No. 3. It is felt that the change in mechanical design made late in this contract period will not meet shock and vibration requirements. This change was the addition of the stainless-steel screen around the isothermal region.
V. DISCUSSION

A. Microcircuit Fabrication

The oscillator microcircuits were initially fabricated using solder reflow to attach the resistors and capacitors. The solder was found to have two disadvantages for this application. Firstly, tin-lead solder diffuses into the gold resulting in undesirable leaching of the gold film. Secondly, complete removal of soldering-flux residue is nearly an impossible task by the limited cleaning techniques available after the components are mounted. It was feared that the flux residue would result in undesirable outgassing in the final package.

To minimize the extent of alloying of the solder on the pre-tinned components with the gold film, special soldering tools were machined to use in soldering the components individually. The manner of soldering was to apply locally a small quantity of flux to the gold film terminals and then position the component to be soldered with a micromanipulator. The substrate, together with the located components, was then placed on a stage heated to approximately 150°C, which is slightly below the reflow temperature of the solder. Additional heat was then applied to each component in turn with the special soldering tools to accomplish the reflow. The process was observed under a microscope and the process stopped as soon as reflowing was complete. Even under these conditions the extent of alloying of the solder with the gold film was quite difficult to control.

It was after experiencing these difficulties that the circuits were assembled using conductive epoxy adhesive to secure and terminate the passive components to the gold film conductors. This type of bond made easy the substitution of components which was necessary during the testing process. Components were removed by local heating with a small soldering tip to soften the adhesive. At first, this method of attaching passive components appeared to be acceptable, but later evaluation showed that many poor electrical bonds were formed. It is now believed that the oxide on the surface of the tinned components is the culprit. Although the terminations were scraped before epoxy was applied, to provide a surface as clean and oxide-free as possible, subsequent heat curing of epoxy probably reformed the oxide barrier between the epoxy and the solder, resulting in an erratic bond. The fact that many of the bonds have been found to be very voltage sensitive supports this hypothesis. All of the components purchased for this contract were pre-tinned and thus we could not attempt the use of epoxy for a gold film to gold termination bond.

We were initially unable to purchase MOSFETS in chip form. In order to meet minimum space requirements, encapsulated (TO-72) chips were dismantled from their holders with leads intact. The chips are extremely fragile and were very easily damaged during handling. Several were lost as a result of handling accidents. Difficulty was also experienced in obtaining reliable bonds between the aluminum leads attached to the MOSFET chips and the gold film. Initially, the aluminum leads were positioned and "tacked" to the gold film with a TC wedge bond, then secured with conductive epoxy adhesive. It was eventually concluded that the TC wedge bonding of the aluminum wire
to the gold film was very unreliable, due to the topographical condition of the gold (too rough) and that the oxide on the surface of the aluminum wire prevented good electrical connection by the epoxy. A solution to this bonding problem is shown in Fig. 33. A gold/chromium film was evaporated onto optically polished fused silica substrates. The substrates were then diced into small chips to form gold bonding pads. The silica bonding pads were then attached to the substrate adjacent to the MOSFET chips. The MOSFET aluminum leads were then TC wedge bonded to the evaporated gold on the polished surface of the bonding pads. A gold wire lead is then TC bonded from the pad to the gold conductor film on the substrate. Although this was quite an involved process, it produced far more reliable electrical connections to the MOSFETs.

Later, MOSFET chips were acquired from RCA without aluminum leads and attempts were made to bond gold leads directly to their aluminum bonding pads. Out of about a dozen attempts, only one MOSFET was successfully bonded into a circuit, Q2, of the TMXO No. 3 oscillator circuit. All other MOSFET connections were made using the process described above. The bonding of gold leads to the aluminum pads of the op-amps has been very unreliable also. Most of the problems experienced with the final operation are believed to be associated with poor lead bonding to the op-amps. The preferred bonding of aluminum in microcircuit fabrication is by ultrasonic welding. The necessary ultrasonic welders were available but not the necessary accessories such as wire feeds and micropositioners.

The improved use of wire bonding techniques would allow the elimination of the conductive epoxy, which is a possible noise source in the oscillator, even under optimum conditions for its use, and allow electrical connection to all components to be by wire bonds. This would probably be the least complicated method of fabrication. Another method for improved fabrication would be the use of solder reflow as originally planned. This, however, would require a different substrate conductor material, e.g., copper, and the use of bonding pads to make electrical connection to the active components. The fabrication of the substrate conductor pattern would require more involved processes in order to tin the necessary area and have gold pads for die bonding the active devices to the substrate.

B. Thermal Runaway

Both Models Nos. 2 and 3 have experienced a similar problem which appears as thermal runaway of the operating temperature at the higher ambients.

Model No. 2 first experienced this problem. After days of operation in vacuum and at high temperatures during insulation tests without any problems, the temperature suddenly ran away and the unit reached a temperature sufficiently high to melt the CERROSEAL solder (softens at 120°C) on top of the crystal holder. As a result, extensive damage was incurred and much repair work was done on this unit. This unit has never operated reliably after that repair. Although some faulty components were found (notably Q2 of the control circuit) it was not known which, if any, caused the problem or if they were the result of the overheating. It was thought that transistor Q2 of the control circuit might be the problem. The method of biasing Q2 is not conducive to high temperature operation. The lack of any emitter resistance tends to make this stage unstable with temperature. Model No. 1 has never run away and no problems were observed in the breadboard after
Fig. 33. Sketch illustrating attachment of MOSFET chip to microcircuit board; (a) initial manner of attaching MOSFET chip to circuit board, (b) modification of attaching MOSFET to eliminate shorting of leads to edge of chip.
many hours of operation without properly heat sinking Q2. Thus there is lack of conclusive evidence that Q2 is experiencing thermal run away although this component is still under suspicion. Another possible cause is some combination of component overheating and resultant lead expansion which leads to an open circuit. The bonding problems have been discussed and control transistor Q2 has been subjected to these problems also. Still another possible cause could be the overheating and expansion of a resistor resulting in a fractured epoxy bond.

Whatever the cause, it is a repeatable occurrence, if not allowed to go too far, which occurs when the units are operated in vacuum and/or high ambient temperatures, although Model No. 3 initially ran away in air at 25°C ambient.

It may be worth noting also that subsequent to one runaway of Model No. 3 it was observed that the input current, during warm-up, indicated a change in the system gain of the control circuit. This is an indication of bonding problems within the control circuit and supports the belief that thermal run away is associated with poor bonds.

C. Insulation and Structural Integrity

The Technical Guidelines for this contract state that the goal for maximum operating power should be 250 mW. The major part of this input power is required to regulate the temperature within the isothermal region. About 30 mW of power is needed to supply the electronics of the present TMXO models. The remainder of the power is required by the heater to make up the thermal losses from the system. In the three prototype models these thermal losses, due to poor insulation, are quite high.

In Model No. 1, which was tested while under continuous evacuation, the major sources of the thermal leakage were due to the stainless-steel support pedestal and improper application of the NRC-2 insulation. The thermal leakages are tabulated below for Model No. 1 under continuous evacuation at -40°C ambient temperature.

1. Convection: Negligible

2. Conduction:
   a. Pedestal: 375 mW
   b. Screen support: 50 mW
   c. Electrical leads: ~10 mW
   d. Total conduction loss: 435 mW

3. Radiation: ~190 mW

4. Total losses: 625 mW

Modifications were made in the construction of Models Nos. 2 and 3 to reduce the operating power to acceptable levels. The stainless-steel pedestal was changed to one of polyimide which reduces the thermal leakage
along this conduction path to about 10 mW maximum. Also, the screen for
supporting the NRC-2 was attached to the polyimide post within the iso-
thermal region instead of to the base. This simple change eliminated the
50 mW loss down the four screen support wires. This change also allowed
the NRC-2 to be applied in a much more suitable manner to reduce radiation
losses. During tests carried out in a vacuum chamber on these two units,
before they were sealed into their outer jackets, it was demonstrated that
the input power levels were below the 250 mW goal. At an ambient of about
+34°C the input powers to models Nos. 2 and 3 were calculated to be about
145 mW and at +75°C ambient about 120 mW. These figures however are not
mutually corroborative in that straight line extrapolation of these power
figures would indicate an operating temperature of about +250°C, which is
inordinately high. These power figures were determined while the units
were immersed in a low pressure (about 5 X 10⁻⁶ torr) bell jar environment.
No data could be obtained for a -40°C ambient because of difficulty in
creating this temperature within the bell jar.

It has now become apparent that it would be extremely difficult to
meet the operating power requirement with the present TMXO packaging
design. This is due to the vacuum incompatibility of a number of materials
being used within the area which must be maintained at pressures less than
10⁻⁹ torr. These materials are limiting the maximum bakeout temperature,
prior to sealing, to about 100°C. To properly outgas any material for long
term low pressure operation requires a very low pressure at temperatures
of 250°C or above. Both Models Nos. 1 and 2 were sealed at low pressure
but outgassing increases the internal pressure to greater than 10⁻² torr
within minutes after the TMXO is turned on.

A review of insulating materials which do not require a low pressure
for their proper use has found no material with a low enough K value to
justify its consideration for this application. The best of these mate-
rials are the plastic foam insulators which have K values of about
2 X 10⁻⁴ W cm/cm² AT. This is one order worse than the calculated K value
needed for the worst case situation (-40°C ambient) of 2 X 10⁻⁵ W cm/cm² AT.

One material we have found which does have possible application is
CAB-O-SIL R*. This material has a reported K value of 2.2 X 10⁻⁵ W cm/cm²-
°C, but it requires a vacuum, like NRC-2, to attain this K value. This
material was rejected after initial tests due to its settling properties
but received further investigation. Model No. 2 was used to conduct the
additional testing of this material. The outside can was placed over the
TMXO and the unit placed in a bell jar vacuum system at 25°C ambient.
Input power readings were then taken under various conditions of insulation
and compared. The results of this experiment are as follows.

<table>
<thead>
<tr>
<th>Insulating Material</th>
<th>Pressure</th>
<th>Operating Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>ATM</td>
<td>900 mW</td>
</tr>
<tr>
<td>None</td>
<td>10⁻⁶ torr</td>
<td>444 mW</td>
</tr>
<tr>
<td>CAB-O-SIL</td>
<td>ATM</td>
<td>660 mW</td>
</tr>
<tr>
<td>CAB-O-SIL</td>
<td>10⁻⁶ torr</td>
<td>242 mW</td>
</tr>
<tr>
<td>NRC-2</td>
<td>ATM</td>
<td>750 mW</td>
</tr>
<tr>
<td>NRC-2</td>
<td>10⁻⁶ torr</td>
<td>150 mW</td>
</tr>
</tbody>
</table>

* Cabot Corporation, Boston, Massachusetts 02110.
The NRC-2 was not supported by a screen during the above experiment. From the tabulated data it is seen that NRC-2 is by far the best material so long as it can be operated in a low pressure environment.

To maintain a pressure of about $10^{-4}$ within a closed system for long periods of time could easily be the most difficult task in future TMXO design. In order to maintain input power levels to less than 250 mW it is imperative that new packaging designs be developed in which the circuitry and other vacuum degrading material are segregated from the insulating medium. The insulating medium should be designed to allow the necessary bakeout temperatures needed for thorough outgassing during evacuation and to allow gettering after sealing. The design should also provide for proper evacuation and sealing of the insulating medium.

One possible design would locate the present crystal-circuitry assembly within a small gas-filled, sealed chamber with high reflectance walls. This chamber, suitably supported, would be centrally located within a larger vessel which would contain only the NRC-2 insulation, getters, support rod for the inner chamber, and the electrical leads from the circuitry to the outside. This area would need to be thoroughly outgassed before making the final seal. After sealing, the getters would be activated to lower the pressure as far as possible. All components not located within the isothermal region would be either external to the unit or located within a third area which would be sealed off from the previous two but part of the whole package. This third area would not be under temperature control or low pressure.

D. Resonators

It was recommended by the Contracting Officer's Representative after Phase I of this contract that we purchase, rather than assemble in-house, the quartz crystal units for this project. Section II-C of this report dealt with some aspects of the resonator performance. From data presented in that section it is obvious that commercial state-of-the-art crystal units cannot meet the desired goals of aging and retrace. The crystals we obtained were plated with aluminum but we have been unable to obtain additional manufacturing information from the supplier. The aging of aluminum plated resonators exposed to various storage temperatures has been described by Belser and Hicklin. They have shown that positive aging vectors predominate at ambient temperatures of 85°C and above, while negative aging vectors become dominant at the lower storage temperatures (45°C and less). It is believed that the crystals being used in the TMXO are behaving in a similar manner, i.e., negative aging when stored at 25°C or less, in a quiescent condition and then aging in a positive direction, at a high drift rate, when the crystal is brought up to operating temperature near 90°C. During each turn-on the crystal repeats its high initial drift. This drift is seen as the offset, after about 20 min, in the warm-up curves of the TMXO.

It has also been suggested that these crystals may be losing their helium, by diffusion or small leaks, during evacuation of the TMXO. The "slim line" HC-6 cold-weld holders used to fabricate these units have not been noted for their sealing ability. In an effort to explain some of the degradation of warm-up time seen in all the TMXO models, data was gathered to see if helium leakage from the crystals was occurring. Figure 34 depicts this data. A warm-up test for Model No. 2 before any evacuation was done on...
Fig. 34. TMXO-2 warm-up comparison before and after unit exposed to vacuum.

Reference taken at 15 min.

After exposure to vacuum

Before exposure to vacuum
this unit was chosen and is compared with a warm-up test after this unit received many hours of evacuation. As seen from Fig. 34, the after evacuation warm-up is actually the better of the two. If any leakage of helium from the crystal can occurred it had to happen before any warm-up tests were performed. This experiment, of course, does not verify that the other two units have not lost some of their helium, but it is now felt that this is unlikely.

E. Calibration

The adjustment methods employed in the temperature and frequency calibrations have worked, in general, but great difficulty was experienced in both. Most of the difficulty has been the frequent rebonding of the adjustment components on the hybrid circuits. The adjustments must be made after the circuits are attached to the crystal holder, which makes the handling of the circuitry more difficult and susceptible to possible damage through excessive handling. Also, the adjustment components are necessarily small and therefore must be designed to be adjusted in discrete steps, which limits the resolution of the calibration.

The desired tuning range, \( \pm 1 \times 10^{-8} \), of the oscillator output frequency has been found to be impractical. Even under optimum calibration the aging and retrace resulting from intermittent operation and extreme variance of storage temperatures of these resonators would result in frequency deviation beyond the range of the adjustment potentiometer.
VI. CONCLUSIONS

The main goals of this contract, as stated by the Contracting Officer's Technical Representative, were volume, power requirements, frequency stability (particularly short term) and warm-up time.

Only the goal regarding volume has been met. We have not been able to meet the power requirements in sealed-off units but have shown that the system is capable of meeting these requirements when a good vacuum is maintained in the insulating space. Maintenance of low pressure in the present package design is not considered feasible.

Although the warm-up time does not meet the goal, the data presented in the section on experimental results indicate that this requirement could be met after employing improved circuit fabrication techniques to increase the reliability of these circuits.

The short term frequency stability is poor in relation to the goals set forth in the Technical Guidelines. There is considerable evidence to indicate that this problem is related to the hybrid microcircuit fabrication and can be rectified by using improved techniques and methods.

On different models the guideline requirements have also been met for frequency/load stability, frequency/voltage stability, frequency adjustment, and output voltage.
VII. RECOMMENDATIONS

A. Resonators

A long term aging requirement of $\pm 1 \times 10^{-10}$/week does not appear to be feasible with commercially available resonators designed for fast warm-up applications. More developmental work is needed in this area. Belser and Hicklin found that aluminum is a poor choice for electrode material if the resonator is subjected to varying storage temperatures. This action leads to various degrees of rate and direction of frequency drift as well as retrace.

B. Electrical Design and Fabrication

The circuit design should be modified for a more practical method of calibrating the operating temperature and frequency. A fine temperature adjustment (potentiometer) is needed before warm-up time can be optimized. Frequency adjustment by one fine tuning control is not practical. Two adjustment controls are needed, one for course adjustment of about $2 \times 10^{-6}$ end-to-end with a $1 \times 10^{-8}$ resolution and the second of about $1 \times 10^{-8}$ end-to-end with a $1 \times 10^{-10}$ resolution.

An obvious shortcoming was the hybrid microcircuit fabrication techniques employed in this contract. There is room for considerable improvement in this area. In addition, the circuits should be located within their own hermetic containers to relieve some of the handling and packaging problems.

C. Package Design

As pointed out in Section V, the power requirement of 250 mW, after warm-up, will be met only by the application of advanced methods of packaging and insulating. That section described one possible approach to this problem. More effort is needed to develop the necessary design concepts and fabrication techniques for the evolution of a sealed insulating medium which can be maintained at the required low pressures over long periods of time. This could be a task which demands separate attention from any future TMXO development.

On the other hand, if the minimum power requirements are relaxed by a factor of 3.5 to 4, it would be possible to fabricate a suitable device using foam insulation. This approach would vastly simplify the construction of the TMXO and eliminate the vacuum requirement, which will continue to remain one of the design uncertainties in future development work.
VIII. ACKNOWLEDGEMENT

The considered help of M. D. Carithers and R. A. Newsom in the experimental work over the past few months of this contract has been greatly appreciated. The past contributions of H. W. Denny, C. S. Wilson and L. C. Young are also recognized.

The help given by Mr. Paul Thorpe, the local Motorola representative, is greatly appreciated. Mr. Thorpe has provided the project with sample quantities of some of Motorola's microcircuit components.
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TACTICAL MINIATURE CRYSTAL OSCILLATOR

The purpose of this work was to develop an experimental tactical miniature crystal oscillator (TMXO) in a $5\text{ in}^3$ volume, use $< 10$ W warmup power from $-40^\circ\text{C}$ to $+85^\circ\text{C}$ in $1$ min, and then operate on $< 250$ mW. It was to reach a maximum deviation from final frequency of $\pm 1 \times 10^{-7}$ after a $1$ min period. The short term stability requirement was to have a maximum rms frequency deviation of $\pm 1 \times 10^{-11}$ for averaging times from $1$ sec to $20$ min.

The TMXO assembly was housed in a stainless steel vacuum container. The temperature sensitive components, i.e., resonator, oscillator and temperature controller, were mounted in the isothermal region of this container. The MOSFET crystal-controlled oscillator and the temperature controller were hybrid microcircuits. Both these circuits and a heating element were epoxy bonded to the resonator can. The temperature sensitive components were insulated from external temperature ambients with aluminized mylar films. Outside the isothermal region was a voltage regulator and a micropotentiometer. The latter had outside access to adjust the frequency within $\pm 1 \times 10^{-8}$.

The overall design concept, while not especially successful in meeting all the performance criteria, did indicate the potential and suitability of this design for constructing TMXO's. Only the goal regarding volume has been met on all models. On different models, however, the guideline requirements have also been met for frequency/load stability, frequency/voltage stability, frequency adjustment and output voltage. Data have been presented which show that both power and frequency requirements could be met, given low pressure operating conditions and improved techniques to fabricate vacuum compatible hybrid microcircuits.
Quartz resonators
Microcircuits
Fast warm-up
Low power
Low aging
Minimum retrace