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5 August 1971

Solid State and Frequency Control Division
Electronic Components Laboratory
U. S. Army Electronics Command
Fort Monmouth, N. J. 07703

Contract No: DAAB07-71-C-0301

Georgia Tech No: A-1344

Subject: Monthly Status Report No. 1 Covering Period 1 July 1971 to 31 July 1971.

Dear Sir:

Various configurations using non-exotic (engineering) materials were considered for feasibility of meeting the operational requirements of the oven-controlled crystal oscillator (OCXO). Heat losses in the Dewar seal plus the heat capacity of the inner Dewar wall proved too great a heat load with an input power of only 250 mW. The possibility of using an evacuated, single-wall vessel containing NRC-2 super insulation to virtually eliminate the transfer of heat by radiation from the centrally located resonator and electronic circuits, each with individual heating elements, appear at first calculation to be a feasible alternate.

Experimental work has confirmed that, while 10 W is enough power to meet the warm-up requirements, the heat losses to the inner walls of the Dewar are too large to meet the minimum power requirement. Resonators sealed in cold-weld holders filled with 50 torr of helium and with an external heating element bonded to the holder cap were placed in the center of standard, one pint, glass thermos and "potted" in place with polyurethane foam. The heater and resonator leads were of .010 inch nickel wire. The can temperature was measured with a No. 30 chromel-alumel thermocouple. The quartz wafer could be heated to 85°C in about 0.5 minutes with 5.5 W. The heating time could be reduced to about 0.25 min by using 10 W but the temperature overshoot was excessive. More important was the power required to maintain 85°C once obtained. The initial power requirement at 85°C was typically 300 mW for an ambient temperature of 25°C; the power decreased with time reaching values near 225 mW after about 30 minutes.

During the month the oscillator design effort has concentrated on circuit techniques for achieving the low source and load impedances necessary

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to minimize the degradation of the Q of the crystal. Amplifiers with input and output impedances on the order of 1 ohm have been realized. Because of large amounts of negative feedback associated with these low impedances, the networks offer high immunity to power supply variations and transistor differences. To minimize the heat load of the electronics, collector currents must remain below 1 mA. At such low currents, sufficiently low input and output impedances cannot be realized with a single transistor. Multistage amplifiers appear to be necessary. Therefore, some type of IC configuration will be required in the final version in order to meet the volumetric requirements.

Oven control considerations to the present time have been primarily concerned with a compilation of literature and technical data information that relate to various circuit configurations and techniques that may be employed in the design of a highly stable oven-control system. In addition, some initial circuit design has been performed and laboratory measurements carried out for evaluation purposes. It is expected that during the coming month a more directive effort will be conducted toward circuit design, construction and careful evaluation of several oven control systems.

Plans for the final month of Phase I include continued theoretical studies of the entire package with respect to methods of meeting the minimum power requirement of 250 mW after warm-up. Problem areas include the conservation of heat at the minimum ambient of -40°C and the "dumping" of the heat produced by the electronics at +75°C ambient temperature.

Also, the circuit design will be examined to determine the effect of terminal impedances on overall oscillator stability in order to determine the minimum acceptable circuit complexity.

This report prepared by L. C. Young, H. W. Denny, C. S. Wilson and W. H. Hicklin.

Respectfully submitted,

Raymond K. Hart (signed)
Project Director

RKH/jl

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January 3, 1972

Commanding General, A15 AAP
U. S. Army Electronics Command
ATTENTION: Solid State and Frequency Control
Division, AMSEL-KL-S
Fort Monmouth, New Jersey 07703

Contract Number: DAAB07-71-C-0301

Georgia Tech Number: A-1344

Subject: Monthly Status Report No. 3, covering the period 1 December to 31 December 1971

Dear Sir:

In order to clear up a number of points raised by Electronics Command personnel regarding the conceptual design for a Tactical Miniature Crystal Oscillator we presented in Report TR ECOM-0301 (INTERIM), several members of our task force visited the U. S. Army Electronics Command on December 1, 1971. In attendance were Dr. E. Hafner, Mr. C. Shibla, Mr. S. Schodowski and Mr. M. Bernstein representing the Electronics Command and Mr. L. Young and Mr. H. Denny from Georgia Tech. This communication is primarily a report of the above meeting and also discusses points raised in Dr. Hafner's letter to Dr. Hart on November 15, 1971.

The three principal topics discussed at the December 1 meeting were:

1. Power consideration when the frequency trimming potentiometer is in the isothermal region of the enclosure and receiving heat directly from the heaters.

2. Vacuum deterioration due to either poor choice of materials for use in the enclosure and/or an inadequate evacuation and bake out, and

3. The design of the oscillator and associated circuitry. Revisions to this very important item have been made by Mr. Denny and a detailed analysis of the new oscillator design is appended to this report.

The frequency-adjustment potentiometer, and especially the HC-6 holder in which it will be housed, is an intolerable load on the heater when the power is limited to 600 watt-seconds for the first minute and 250 mW thereafter. When the operation of this potentiometer is taken into account, one reaches the conclusion that temperature control is not really needed. The end-to-end value of the "pot" only determines the current drain on the power supply. The important parameter is the ratio of the portions above and below the adjustable tap. This ratio would likely not change with temperature even though the end-to-end value changed. The frequency trimming pot will be moved out of the isothermal zone to a position on the type D holder base. The general scheme for obtaining access to the adjustment screw will be the same.

The NRC-2 Super Insulation to be used in the type D holder is most effective at pressures of about 10^{-4} torr or lower according to the literature. We may be able to allow the pressure to rise as much as two orders without serious difficulty. However, pressure higher than 10^{-2} torr will certainly make the heat loss, through gaseous conduction or convection, intolerable. The solution would seem to be:

1. The selection of vacuum compatible materials for all active, passive and supporting parts,

2. Include along with the required parts a solid getter to "soak up" gases as they are evolved during the life of the device, and

3. Evacuate to a very low pressure (10^{-7} torr or less) and bake at the highest possible temperature for about 24 hours before the final seal is made by cold welding.

There are two solid getters that we know about. Cerralloy 400 Getter (Ronson Metals) is easy to install, chemically and mechanically stable; however, it is effective only at temperatures well above normal room temperature. Solid barium getter tablets (Linde) are effective at room temperature but easily broken and the resulting chips would be a potential source of electrical short circuits or capacity changes, both of which are intolerable. Both of these materials are on hand although we are planning to return the barium tablets to the supplier because of their unsuitable character.

All materials of questionable vacuum compatability will be tested under normal operating conditions. Otherwise, it would be expedient to accept the outgassing data of reputable manufacturers, usually expressed in terms of weight loss per unit time at an elevated temperature in vacuum.

One item in Young's trip report mentioned the use of "CAPTON." This is probably the polyimide made by du Pont under the trade name KAPTON. We are aware of the excellent properties of the polyimides and have it on order. However, according to the local du Pont office, KAPTON is only made as a film or sheet. The solid shapes (rods, etc.) are sold as VESPEL. The unmodified base resin, SP-1, has excellent electrical and mechanical properties as well as low thermal conductivity and may be used to support the isothermal core. Polyimide is sometimes confused with polyamide. The latter includes nylon and similar plastics.

Work has progressed on fabricating a suitable containment vessel which can be cold welded to the type D cold weld bases. Rather than go to the expense of having a few (about 12) vessels made by a deep drawing process, we are using the 5/8-inch high caps which were supplied with the bases.† These caps are being cut in two and a stainless steel insert added to bring the total height to 3 1/4-inches. Sealing these joints is done by TIG welding. We are also investigating the possibility of brazing these two joints. This may prove to be cheaper than TIG welding yet just as effective.

The voltage regulator may have to be under at least partial temperature control. Regulators having a low temperature coefficient of reference voltage are available; for example, the RCA CA 3055 has a coefficient of .0025%/°C. The voltage change for a 115°C temperature change would be about 0.03 volts with a nominal 9 V output, a small but not negligible amount considering that this voltage is applied to the frequency trim pot. Young's trip report stated that Dr. Hafner did not favor an "in-between position," for the regulator. However, if the regulator is not in the isothermal region, it should at least be insulated from the ambient so that the power dissipated by this active device could reduce the effect of the -40°C temperature. If then the final adjustment of the regulated voltage is made at about 35 to 40°C, the effects of the temperature extremes may be reduced sufficiently. Actually, we would prefer to use a simpler voltage regulator. Voltage regulators such as the one cited above require a considerable amount of external circuitry to be added to an already overburdened electrical and thermal load.

The isothermal core will contain the most sensitive parts of the device with respect to frequency. Thus, the mechanical stability of the core is very important. Changes in the core position due to rotation could cause capacity changes which in turn would cause frequency shifts. The core mounting method will insure that rotation is not possible.

Reference paragraph 2.3.2.1 of the Technical Guide Lines; an input voltage variation of 1.2 V is permitted (11.4 to 12.6 V). However, the nominal input voltage is 12 V and the associated input power 10 W. The latter values of voltage and power will be used in future reports to eliminate ambiguities.

During the first minute after turn on, the entire 10 W will in effect be dumped into the heater circuit. This action will occur because the heater control transistors are biased into saturation and represent a short circuit between the low-resistance heater and 12 V power supply: Power drawn by other

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†We were unable to obtain Type D cold weld holders commercially. Mr. R. J. Byrne of Bell Telephone Laboratories very kindly furnished 24 bases and caps.

components will be negligible. However, after one minute, the total input power must be reduced to 250 mW maximum. The 250 mW value is the power drawn by all components including the op amps of the temperature control circuitry. A figure showing the basic electrical circuits prepared for the interim report but not used is included as Figure 1 of this monthly letter report.

The relation between Figures 11, 12a, and 12b in report TR ECOM-0301 (Interim) is the following:

1. Figure 12a represents the first two blocks of Figure 11, the temperature sensitive bridge and the low-gain op amp.

2. The output of the op amp in Figure 12 a should be changed from V_0 to V_1 since it supplies the input, V_1, of the op amp with the temperature sensitive gain shown in Figure 12b.

3. The output V_0 in Figure 12b provides the base drive for the control transistors in series with the heater. The latter two components are represented by block 4 in Figure 11.

The following errors were noted by Electronics Command personnel in the Report Number TR ECOM-0301 (INTERIM):

1. Page 5, 2nd paragraph, line 10; -7°C rather than -12°C.

2. Page 8, section 1-b, Superinsulation NRC-2, 1 layer should read . . . 16 layers.

3. Page 10, line 9, 0.036 cm rather than 2.036 cm.

4. Page 12, equation (1), use t rather than T for left side of the equation.

5. Page 12, line following equation (1), t rather than T.

We recommend that all copies of the cited report be corrected as indicated above.

Work to be performed during January include:

1. Construction of a cold-weld die for the type "D" holders from an already-completed design.

2. Assembly and testing of components. Both electrical, thermal and mechanical testing will be made on subassemblies as well as on the completed package. Equipment to carry out these tests has been set up in the laboratory and calibrated.

3. Continue with procurement which is becoming a problem. We considered it premature to complete our procurement, especially on the electronic components, during July, August and September. October and November were dormant months during which time no material requests could be submitted. We continued the procurement starting 1 December 1971. However, we find that delivery schedules are longer than anticipated. For example, almost one-third of our remaining time will elapse before all the crystal units are delivered from the supplier. We have requested that each crystal unit be shipped as soon as it has passed acceptance tests.

Contracted during the month of December 1971 were two modifications to Contract DAAB07-71-C-0301. These were as follows:

Vibration Testing; DAAB07-72-Q-0169	$ 169.00
Evaluation Reports; DAAB07-72-Q-0122	$1,344.00

These additions will be added to the initial contract budget in the December Cost and Performance Report. The C & P report will be forwarded under separate cover about the middle of January or as soon as our accounting sheets become available.

Respectfully submitted,

Raymond K. Hart
Project Director

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enclosure

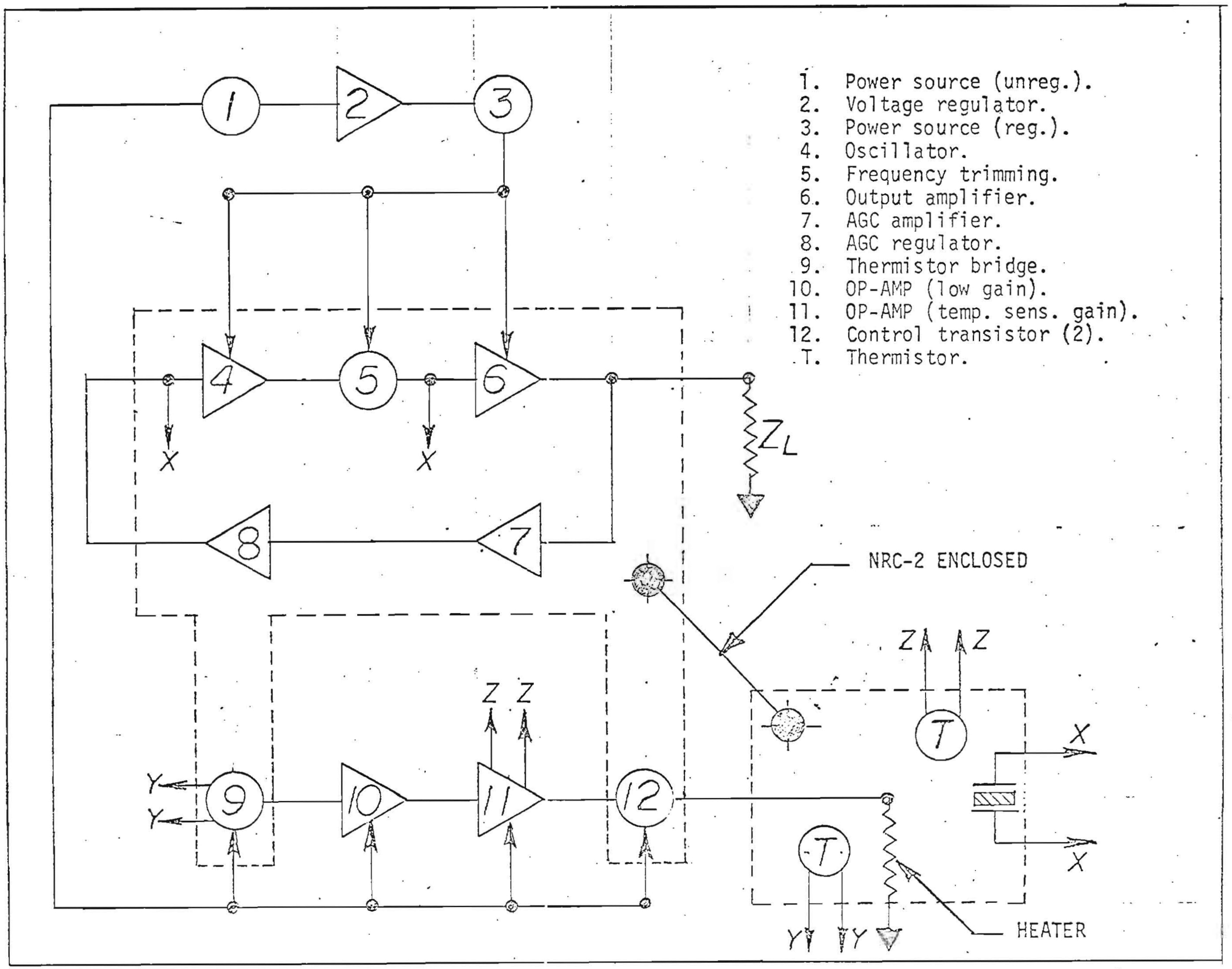


Fig. 1 Symbolic presentation of all electrical circuits and components within the OCXO.

APPENDIX I

OSCILLATOR CIRCUIT DESIGN

During the month, an intensive effort was directed toward the development of the detailed design of the oscillator sub-assembly of the OXCO. The initial task consisted of a re-examination of the primary conclusions that were presented in Section 4.4 of the Interim Technical Report. On page 30 of the report, a rather large change in capacitor C_2 in the frequency-determining loop was concluded to be commensurate with a frequency-adjustment range of 1×10^{-8}. A further evaluation showed that equation 10 on page 30 was wrongly applied to evaluate the effects of capacitor C_2. Since C_2 is smaller than C_3 (for $h > 1$), changes in C_2 should have a correspondingly greater effect on the loop resonant frequency than the same changes (magnitude not percentage) in C_3. In recognition of this fact, an alternate approach to a frequency vernier was developed. A practical technique was developed for tuning the frequency 1×10^{-8} with a resolution of 1×10^{-10} with currently available varactor diodes. Many interrelated factors must be considered, however, before the frequency vernier technique is described. Therefore, it is appropriate to consider the frequency vernier network along with several other aspects of the oscillation design.

Crystal Drive Level. For best long-term stability, low crystal drive levels are necessary. Hafner[1] has shown, however, that the short-term stability is inversely proportional to the drive level according to the following relationship:

$$\frac{\Delta f}{f} = \frac{2\pi}{\tau} \sqrt{\frac{4KT}{PQf}} \qquad (1)$$

where τ is the sampling time, K is Boltzman's constant, T is the temperature in degrees Kelvin, P is the crystal drive power, Q is the crystal's Q, and f is the resonant frequency.

Previous tests at Georgia Tech[2] have shown crystal currents between 100 μA and 400 μA offer a good signal-to-noise ratio without excessive sensitivity to drive level variations. The effective series resistances, R_e, of 5 MHz fundamental resonance crystals with 32 pF load capacity can be expected to be between 5 and 10 ohms. A maximum series resistance of 10 ohms was assumed and calculations of crystal dissipation were made for crystal currents of 200, 300 and 400 μA. The following short-term stabilities were then computed from equation (1) assuming a 1-second sampling time:

Crystal Current (μA)	Drive Level (μW)	$\Delta f/f$ (1×10^{-12})
200	0.3	1.0199
300	0.675 (R_e = 7.5Ω)	0.6799
316	1.0	0.5580
400	1.6	0.4416
3,160	10.0	0.1766

(1) E. Hafner, "Stability of Crystal Oscillators," Proceedings of the 14th Annual Symposium on Frequency Control, 1960, pp. 192-199.

(2) R. B. Belser and W. H. Hicklin, "Quartz Crystal Aging Effects," Technical Report, ECOM-02251 (E)-9, September 1965.

These results indicate that crystal dissipation is not expected to be the factor which limits the short-term stability. Crystal current becomes more important in terms of the signal voltage available at the output of the pi network and the drive signal which must be supplied by the oscillator transistor than in terms of crystal dissipation.

Pierce Oscillator. The crystal pi network is the primary element of the oscillator. Figure 1 shows the equivalent circuit of the pi network. In this figure, L_e represents the equivalent inductance of the quartz resonator. R_e is the effective series resistance of the crystal at loop resonance, i_x is the crystal current and i_i is the input current supplied by the oscillator transistor to the pi network.

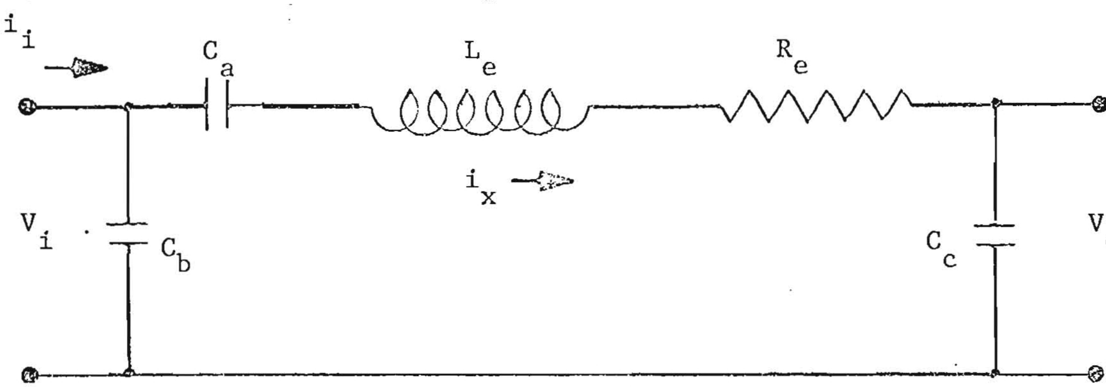


Figure 1. Equivalent Circuit of the Pi Network at the Resonant Frequency

A large number of combinations of C_a, C_b, and C_c will produce a resonant circuit. To select a particular combination of values, various trade-offs must be investigated. The load capacity, C_x, presented to the crystal by the three capacitors in series must be chosen. At the natural resonance of the crystal, the reactance, X_e, of the crystal is zero. The effect of the load capacity is to shift the frequency to the point where X_e of the crystal equals the reactance of C_x. Low values of C_x, i.e., high load reactance, produce relatively large shifts from the natural resonant frequency. Large frequency shifts are accompanied by significant increases in R_e which effectively degrade the Q of the resonator and increases in the power dissipation in the crystal. A large C_x, though producing less of a frequency shift, lowers the circuit resonant impedance and increases the signal current which must be supplied by the oscillator transistor.

A frequently suggested value for C_x is 32 pF. Because 32 pF is commonly used and because of the need to place the order for crystals with the manufacturer as quickly as possible, the load capacity was tentatively chosen as 32 pF. However, to make sure that 32 pF represents the preferred or, at least, an acceptable choice, the performance characteristics of the pi network were analyzed for values of C_x of 20, 30, 32, 50 and 100 pF. For each of these values of C_x, the voltage attenuation through the network was calculated for nominal values of C_c from 500 to 2000 pF and for ratios of C_c to C_b of 1, 5 and 10. These calculations showed that some combinations required impractical values of C_a or required negative values of C_a. Fortunately, at C_x = 32 pF, a fairly flexible choice between the values for C_a, C_b and C_c is possible without requiring more gain than a single transistor can provide.

Transistor input and output capacitances were included in the analysis by assuming that C_b is the sum total of a fixed capacitor and the output capacity of the oscillator transistor and that C_c consists of a fixed capacitor in parallel with the two base capacitances of the oscillator transistor and the buffer amplifier. The terminal capacitances of transistors are likely to be functions of the operating point, supply voltage, etc. Therefore, it is highly desirable that the passive portions of C_b and C_c be large enough to effectively swamp out the effects of the transistor terminal capacitances.

The input and output impedances of the 2N918, 2N2222A and the 2N5828 transistor types were measured at collector currents (I_c) from 50 to 500 μA. Of the three transistors, the 2N918 exhibited the highest equivalent parallel resistance and the lowest equivalent parallel capacitance at both input and output. At 300 μA collector current, the equivalent parallel input capacity of the 2N918 varies from 38.5 pF with the emitter grounded to 28.2 pF with 47 Ω unbypassed emitter resistance. The input capacity of the 2N918 is essentially the same as that of the 2N5828; both exhibit a lower input capacitance than the 2N2222A at corresponding collector currents. The real part of the input impedance of the 2N918 is approximately 2 times that of the 2N5828 and thus the 2N918 is the preferred choice. In addition, the voltage gain exhibited by the 2N918 is slightly higher than that exhibited by the 2N5828.

The following tabulation shows the input and output characteristics of a common emitter amplifier employing a 2N918 at 300 μA collector current:

R (Ω)	R_i (Ω)	C_i (pF)	R_o (Ω)	C_o (pF)
0	670	38.5	10,900	7.1
10	740	35.8	10,900	7.1
22	809	33.0	11,100	7.1
47	980	28.2	11,200	7.0

R is the unbypassed emitter resistance . R_i is the equivalent parallel input resistance. R_o is the equivalent parallel output resistance. C_i is the input capacitance and C_o is the output capacitance.

Since C_c must include the effects of two transistors, that portion of C_c contributed by the transistors may be as much as 75 to 80 pF. C_b must include the effects of only one transistor output capacitance which amounts to 7 pF. To minimize the effects of the transistor capacitances on loop stability, it was deemed desirable to make C_b and C_c large enough to permit the portion of the total capacity provided by lumped capacitors be at least 10 times that contributed by the transistors. This means that C_b should be at least 77 pF and that C_c should be 880 pF or larger. Nominal values of 100 pF for C_b and 1000 pF for C_c were selected. For C_x = 32 pF, C_a then must equal 49.38 pF. With these values of C_a, C_b, and C_c, the required voltage gain of the oscillator transistor is 21.25.

The reactance of 1000 pF at 5 MHz is 31.8 ohms which is less than one-tenth the resistance seen looking into the bases of two 2N918's in parallel. Thus the output voltage, V_o, of the pi network is approximately i_x X x_{c_c}. The signal voltage developed across C_c is 6.36 mV rms for i_x = 200 μA and 12.72 mV vms for i_x = 400 μA. Either voltage is considerably above the noise threshold of the 2N918.

The signal current, i_i, which must be supplied by the oscillator transistor is 13.35 μA for an i_x of 200 μA. The required signal voltage at the input to the pi network is

$$V_i = V_o \text{ X } A_v = 6.36 \text{ X } 21.25 = 135 \text{ mV}.$$

Thus impedance at the input to the pi network is

$$Z_{i(\pi)} = \frac{V_i}{I_i} = \frac{135 \text{ X } 10^{-3}}{13.35 \text{ X } 10^{-6}} = 10.1 \text{ K}\Omega.$$

If a collector resistance of 10 KΩ is assumed, the net signal load impedance, Z_c, which must be driven by the transistor is 5 KΩ. At 300 μA collector current, the 2N918 provides a voltage gain of 24 into a 4.7 KΩ load.

For i_x = 400 μA, the input current i_i increases to 26.7 μA. Since the output voltage of the pi network doubles, the signal voltage developed at the collector increases by 2. The load impedance seen by the collector does not change, and the total signal current, i_s, increases from

$$i_s = \frac{V_i}{Z_c} = \frac{135 \text{ X } 10^{-3}}{5 \text{ X } 10^{+3}} = 27 \ \mu\text{A}$$

to

$$i_s = \frac{270 \text{ X } 10^{-3}}{5 \text{ X } 10^{3}} = 54 \ \mu\text{A}$$

which is still well within the linear region of the 2N918 at 300 μA collector current.

Up to this point a collector resistance of 10 KΩ has been implied. At 300 μA collector quiescent current, 10 KΩ properly sets the collector voltage at the point which permits the maximum expected peak-to-peak signal swing to be achieved with neither saturation nor cutoff of the oscillator transistor. Further, since the 10 KΩ resistance in parallel with the input of the pi network presents a realistic load to the transistor, 10 KΩ is deemed a reasonably appropriate collector resistance.

Figure 2 shows the complete schematic of the oscillator to include the buffer amplifier, the AGC network, the frequency vernier, and a remote sensor for improved voltage regulation. The values shown for C_a, C_b, and C_c are nominal values. The value of C_x necessary to trim the crystals to within 1×10^{-8} of 5 MHz will not be exactly 32 pF. Consequently, the capacitance values may necessarily depart from the values shown. Calculations have shown that C_a and C_b may deviate ± 10 per cent from the nominal values illustrated without exceeding the gain capabilities of the 2N918.

Buffer Amplifier. In order to restrict the power consumption requirements of the buffer amplifier to acceptable limits, the load seen by the buffer amplifier must be no less than 1000 ohms. The buffer amplifier design is predicated on an external load, R_L, of 1000 ohms.

The required output signal voltage is 125 mV rms or 354 mV p-p. With R_L = 1000 Ω and V_o = 360 mV p-p, the following gain characteristics were measured with 2N918's:

Collector Current (μA)	Voltage Gain	Distortion
200	4.5	Significant
300	7.8	Minimal
400	10	None

The avoidance of excessive distortion in the output signal is deemed highly desirable; therefore, 200 μA collector current is too low. At 400 μA, the amplifier gain is 10 which would require an input voltage of 12.5 mV. At 400 μA crystal current, the voltage available at the input to the buffer would be 12.72 mV with C_c = 1000 pF. Rather than use a single amplifier which would necessitate operating at the higher limit of crystal current, the use of two amplifier stages, Q_2 and Q_3, is expected.

The output amplifier will be operated at a collector current of 300 μA and the first stage will be biased for a collector current of 100 μA. The 2N918 exhibits a voltage gain of 3 for I_c = 100 μA. Thus the overall voltage gain provided by the two-stage buffer is

$$3 \times 7.8 = 23.4.$$

The input signal requirement is now reduced to 5.35 mV which allows greater flexibility in the choice of crystal operating current and permits some deviation in C_c from 1000 pF if required.

The use of two stages provides additional isolation between the load and the crystal pi network. In addition, the AGC amplifier can be tapped into the circuit between the two buffer stages and thus reduces by one the number of transistor inputs across C_c. Further, the gain provided by the first buffer stage lessens the gain requirements of the AGC amplifier.

The collector resistance of 10 KΩ sets the transistor operating point such that both saturation and cutoff are avoided when developing 125 mV across 1000 Ω.

<u>AGC.</u> The AGC loop consists of amplifier Q_4, a voltage doubler D_1 and D_2, transistor Q_5. AGC of the oscillator is obtained by varying the base biasing resistance. Varying this resistance moves the base bias point of Q_1 up or down to change the oscillator collector current which in turn varies the transistor gain. Other potential AGC techniques, such as varying the unbypassed emitter resistance of Q_1, required the realization of variable resistances not readily achievable with conventional FET's or with bipolar transistors without excessive collector currents.

Q_4 is biased at a collector current of 100 μA. At 100 μA, the measured gain of a 2N918 into a high impedance load is 8. Since the first buffer stage, Q_2, provides a gain of 3, the total AGC amplifier gain is 24. The peak voltage available at the output of Q_4 is

$$5.35 \times \sqrt{2} \times 24 = 182 \text{ mV}$$

which is too low to be detected by diodes D_1 and D_2. Since the impedance looking into the rectifiers is very high, a 10:1 step-up transformer may be used to increase the RF voltage to 1.82 volts peak which is more than adequate to switch the diodes. Since the signal currents involved are very low, a transformer capable of providing the 10:1 step-up can be realized in the very small configuration which is required.

The dc output of the rectifier will be

$$2 \times 1.82 - 2V_f$$

where V_f is the forward drop of the diodes. Assuming an operating temperature of ±85°C, V_f is typically in the neightobrhood of 0.3 volts. Therefore, the dc voltage available for AGC control is 3.04 volts. Using a 2N5828 for Q_5 because of its very high dc gain properties at low collector currents, a base voltage of approximately 0.5 volts was found to be required to set the collector current of Q_1 at 300 μA. This 0.5 volt value may change slightly depending upon the values of the base biasing resistors of Q_1. However, it is adequate for design purposes. Measured variations in I_c of Q_1 versus control voltage into the base of Q_5 showed an equivalent gain of 5. Thus a net AGC loop gain of 120 or 41.6 dB is predicted which should provide close control over the oscillator operating level.

<u>Frequency Vernier.</u> It was shown on page 30 of the Interim Report that a change in frequency of 1×10^{-8} corresponds to a change in C_x of 4.3×10^{-3} pF for $C_x = 32$ pF. Since C_c is the largest capacitor in the pi network and thus

contributes the least to C_x, a variable capacitor in parallel with the fixed capacitor(s) represents the most practical approach to a frequency vernier. The following tabulation shows the amount, ΔC, by which C_c must be varied to produce a 4.5×10^{-3} pF change in C_x:

C_c (pF)	C_b (pF)	C_a (pF)	C_x (pF)	ΔC (pF)
800	80	57.1	31.999	2.82
900	90	52.5	31.998	3.57
1000	100	49.4	31.998	4.41
1200	120	45.3	31.998	6.36

This tabulation shows that a nominal variation of 5 pF in C_c is required. Motorola's MV2101 is a possible choice of a varactor diode to provide this tuning adjustment. This diode exhibits a capacitance change of from 10 pF at 1 volt reverse bias to 5 pF at 9 volts reverse bias for a capacitance-voltage gradient of 5 pF/volt. At low bias voltages, the Q of the varactor decreases significantly. Therefore, it is preferable to use a larger capacitance diode and obtain the 5 pF increment with a smaller voltage change. The MV2109 appears to be adequate for this purpose. This diode exhibits a capacitance variation from 55 pF at 1 volt reverse bias to 25 pF at 9 volts reverse bias. A bias change from 4 volts to 6 volts changes the capacitance from 35 to 30 pF for a capacitance-voltage gradient of 2.5 pF/volt. The diode is thus kept away from its low Q region and, in addition, the bias voltage is several orders of magnitude greater than the RF signal voltage across the diode which avoids any possibility of diode switching.

If an 11-turn potentiometer is used to vary the bias voltage over the 2 volt range, each full turn of the potentiometer will produce 0.182 volts change in varactor bias. At 2.5 pF/volt, then each turn will change the capacitance 0.455 pF; the 4.3×10^{-5} change in C_x that corresponds to 1×10^{-10} resolution will therefore require 0.11 turn or 40 degrees of shaft rotation.

Supply voltage variations can cause frequency changes because of the changes produced in the varactor capacitance. For this reason, a very high degree of voltage regulation will be necessary. For example, since a ΔC of 0.05 pF represents a frequency change of 1×10^{-10}, the capacitance variation due to voltages changes should be limited to at least .005 pF. At 2.5 pF/volt, a voltage stability of ± 0.002 volts would be required. On a 9 volt supply, a voltage change of 0.002 volts represents a voltage regulation of 0.02.

The temperature coefficient of Fairchild's μA723 regulator is given as 0.002%/°C, typical. Since the regulator must be located outside the isothermal region of the oven because of its relatively high power consumption, the regulator must be assumed to operate over a temperature range of up to 115°C. Therefore, the output voltage may change as much as 0.23%.

To achieve the needed 100:1 improvement in the voltage regulation, it is planned to provide a sampling network and a high gain, low quiescent power drain, op amp such as Fairchild's µA776 mounted on the oscillator substrate. Precision, low T.C. resistors will be used to sample the oscillator supply voltage. Variations in this voltage will be amplified by the op amp and will be used to correctly adjust the output of the voltage regulator to compensate for the changes caused by temperature variations of the regulator.

Component Considerations. Chip capacitors are available with reasonable delivery time to provide all needed circuit functions. All bypass and coupling capacitors can be 0.01 µF general purpose capacitors. Capacitors C_a, C_b, and C_c, however, must exhibit at least an NPO temperature characteristic of ± 30 ppm/°C or less. For the nominal values of C_a = 50 pF, C_b = 100 pF, and C_c = 1000 pF, and if all capacitors exhibit same temperature coefficient of +30 ppm/°C, the frequency change expected for a 0.01°C change in the oscillator circuitry was calculated to be 2×10^{-11}. The temperature coefficient of the varactor may be as much as +400 ppm/°C, depending upon the bias voltage. However, because of the relatively low contribution of the varactor, including the effects of the temperature variation, the total value of C_x did not significantly increase the frequency deviation. The frequency change expected from a 0.1°C temperature change was calculated to be on the order of 2×10^{-10}.

These changes are well within the limits demanded over the 115°C variation in ambient temperature. Thus it appears that the oscillator circuitry could vary in temperature at least as much as 0.1°C and still retain the desired frequency stability.

A thin film resistor is available from Motorola that exhibits a much improved TCR over that offered by the Mini-Systems type MSR-1 resistor. In order to restrict the current requirements of the biasing networks, relatively high ($\geq$ 100 KΩ) resistance values are necessary. The conventional hybrid circuit chip resistors such as the MSR-1 exhibit rather poor TCR's in high resistance values. The nichrome films used in the thin-film resistors, however, can exhibit TCR's approaching 0 ppm/°C at high resistances. The chip configurations are such that tap points are available which is highly desirable when resistances having matched TCR's is required. For example, if the two resistors of the base-biasing voltage divider have the same TCR the bias voltage does not vary with the temperature of the resistors.

Bias Current Requirements. At +85°C, the 2N918 exhibits a dc beta of 50. For 300 µA collector current, the base current required is only 6 µA. For good stability, the current through the base biasing resistors should be much larger than the base current. A nominal bias current of 50 µA should be adequate to stabilize the bias point. The sum of the two resistances constituting the base biasing network for transistors Q_1, Q_2, Q_3 and Q_4 will be 180 KΩ.

Although less bias current could probably be tolerated, the higher resistances associated with the lower currents might be inconvenient to realize because the highest resistance obtainable in a single thin-film resistor is 100 KΩ.

Bias current is also required for the op amp used to improve the voltage regulation. Up to 100 μA is assumed to be necessary for this purpose. Fifty μA is estimated to be adequate for the frequency vernier potentiometer.

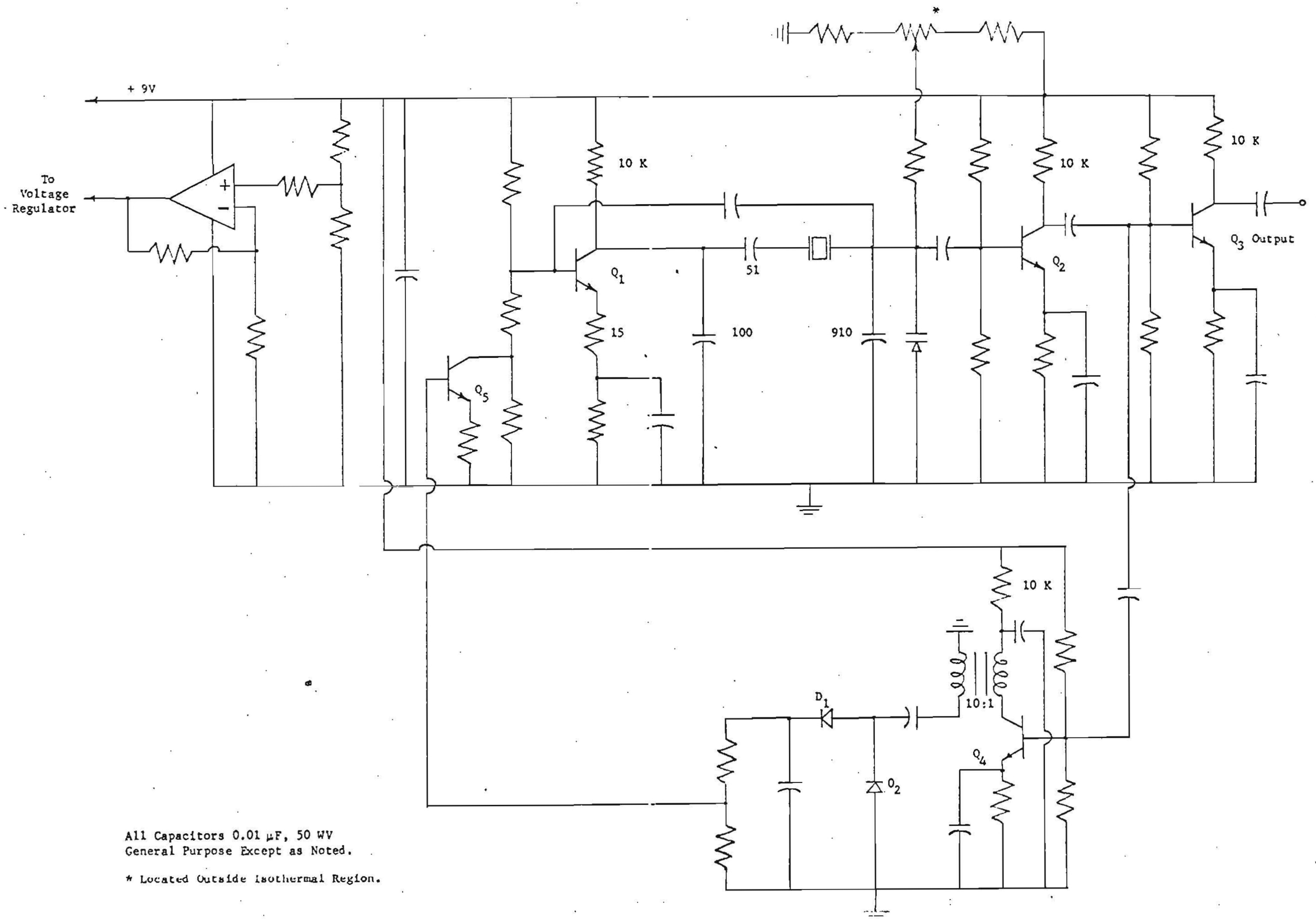
<u>Total Power Requirements.</u> The current requirements in μA of all elements of the oscillator are as follows:

Oscillator (Q_1) Collector Current		300
Buffer Amplifier (Q_2)		100
Buffer Amplifier (Q_3)		300
AGC Amplifier (Q_4)		100
Bias Currents (4 @ 50 μA)		200
Op Amp		100
Frequency Vernier		50
	Total	1,150

The power dissipation of the oscillator network is

$$P_d = 9 \text{ X } 1.15(\text{mA}) = 10.35 \text{ mW}$$

which is close to the 10 mW goal established earlier.



All Capacitors 0.01 μF, 50 WV
General Purpose Except as Noted.

* Located Outside Isothermal Region.

Figure 2. Oscillator Schematic Diagram.

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February 3, 1972

Commanding General, A15 AAP
U. S. Army Electronics Command
ATTENTION: Solid State and Frequency Control
Division, AMSEL-KL-S
Fort Monmouth, New Jersey 07703

Contract Number: DAAB07-71-C-0301

Georgia Tech Number: A-1344

Subject: Monthly Status Report No. 4 covering the period 1 January to 31 January 1972

Dear Sir:

During this report period we have accomplished the following:

1. Completed an oscillator design that uses MOSFET rather than transistor amplifiers.

2. Constructed the oscillator as in (1) in breadboard form and evaluated its performance at 85°C.

3. Completed the MOSFET oscillator circuit hybrid-form layout and started the art work. Procurement of chip resistors and capacitors was initiated.

4. Built the first breadboard model of the temperature control section and evaluated its performance at 25°C with a crystal unit and attached heater potted in insulating foam.

5. Completed a die, except for hardening, for the cold-weld sealing of type "D" holders.

During a visit to Fort Monmouth on January 18, 1972, Dr. R. K. Hart and Mr. W. H. Hicklin gave Mr. C. L. Shibla a copy of a circuit diagram for a MOSFET crystal oscillator designed and built by Mr. L. A. Phillips, who is presently assigned to this project. The design has since been improved as well as the addition of a frequency-trimming varicap and associates biasing network. The present circuit is shown here as Figure 1. The circuit changes were made mostly to increase the load isolation. Circuit additions include C_1 a Motorola type MMCQ101 for coarse frequency trimming during final adjustment and the varicap and associated biasing circuit. The varicap for the breadboard model is a Motorola MV-1650. Since the latter is not available in chip form a substitution will be made on the hybrid circuit. Most of the operating parameters are shown with Figure 1. The input power, 9 mW, is for the two-stage oscillator-amplifier only. We are now trying to obtain the RCA 40673 MOSFET in chip form rather than as an encapsulated unit.

The transistor oscillator shown in Figure 2 of Progress Letter No. 3 was built concurrently with the experimental work on the MOSFET oscillator. The performance was erratic, especially with regard the AGC operation. This circuit has since been modified by Mr. H. W. Denny and now appears to be feasible should we need to use it. However, phone calls on January 24, 1972, to Dr. Hafner and Messrs Shibla and Schodowski have resulted in a qualified okay to proceed with the MOSFET oscillator.

Mr. M. D. Carithers has completed the layout work for the reproduction of the MOSFET oscillator on a 1/2" X 5/8" alumina wafer. Reproducing the artwork on Amberlith is the next step; a 50:1 scale will be used with subsequent photographic reduction to 1:1 for the photoresist exposure mask. Standard photoengraving techniques will be used to produce the chromium-gold conductor pattern and the resist will be KTFR. The oscillator circuit will be completed during the next month provided we obtain the chip components which are now on emergency order. A detailed report of the hybrid layout will be included in the next progress letter.

The first model of the temperature control circuit has been built. The optimum level of gain is currently being studied at room temperature under rather primitive conditions compared to the final encapsulation in vacuum with NRC-2 insulation. The circuit follows very closely the block diagram shown in Figure 11, page 35 of report No. TR ECOM-0301 (Interim) except that the control transistor is in the Darlington configuration and has a voltage gain of about 30. The first OP AMP stage has a voltage gain of about one. The gain of the second stage can be controlled by varying the value of the feedback resistor. The following table gives the frequency instability due to the thermal hunting effect with second stage gain of various values.

Gain of Second Stage	Peak to Peak Frequency Deviation ($\Delta F/F$)
4	4.0×10^{-8}
10	7.0×10^{-8}
25	1.6×10^{-7}
100	5.0×10^{-7}

The frequency variations are not random. They are apparently the result of too much gain, even at the lowest value. In any case, the circuit is not yet final and will not be reported in detail until later. The results at this point are very encouraging. The warmup time to ~85°C is about 40 seconds with an input power level of 7.2 W. We ordered heating elements with 15.8 ohms resistance so the input power would not exceed 10 W with the full voltage (12.6 V) across the terminals. Thus, the heater power drain will always be less than 10 W. The operating power after warmup is about 480 mW. However, we presently have eleven copper leads connecting the crystal, heater, thermistors, etc., to the external circuits. In the final assembly all but two or three leads will be interconnections in the isothermal zone.

A cold-weld die for sealing type "D" holders with the upper section 3 1/2 inches tall was built of No. SAE-01 oil hardening tool steel. The hardening process for producing a $R_W C$ hardness of about 59 has yet to be done.

Work during the next month will consist of the following:

1. Transform the breadboard MOSFET oscillator to a 1/2" X 5/8" hybrid wafer.

2. Continue measurements and modifications of the temperature control circuits.

3. Study the mechanical characteristics of various core mounting systems. Strictly mechanical considerations recommend stainless steel as the support material. However, thermal considerations suggest the use of a plastic such as Vespel. The vibration equipment will be used to check potential designs.

Respectfully submitted,

Raymond K. Hart
Project Director

RKH:cc

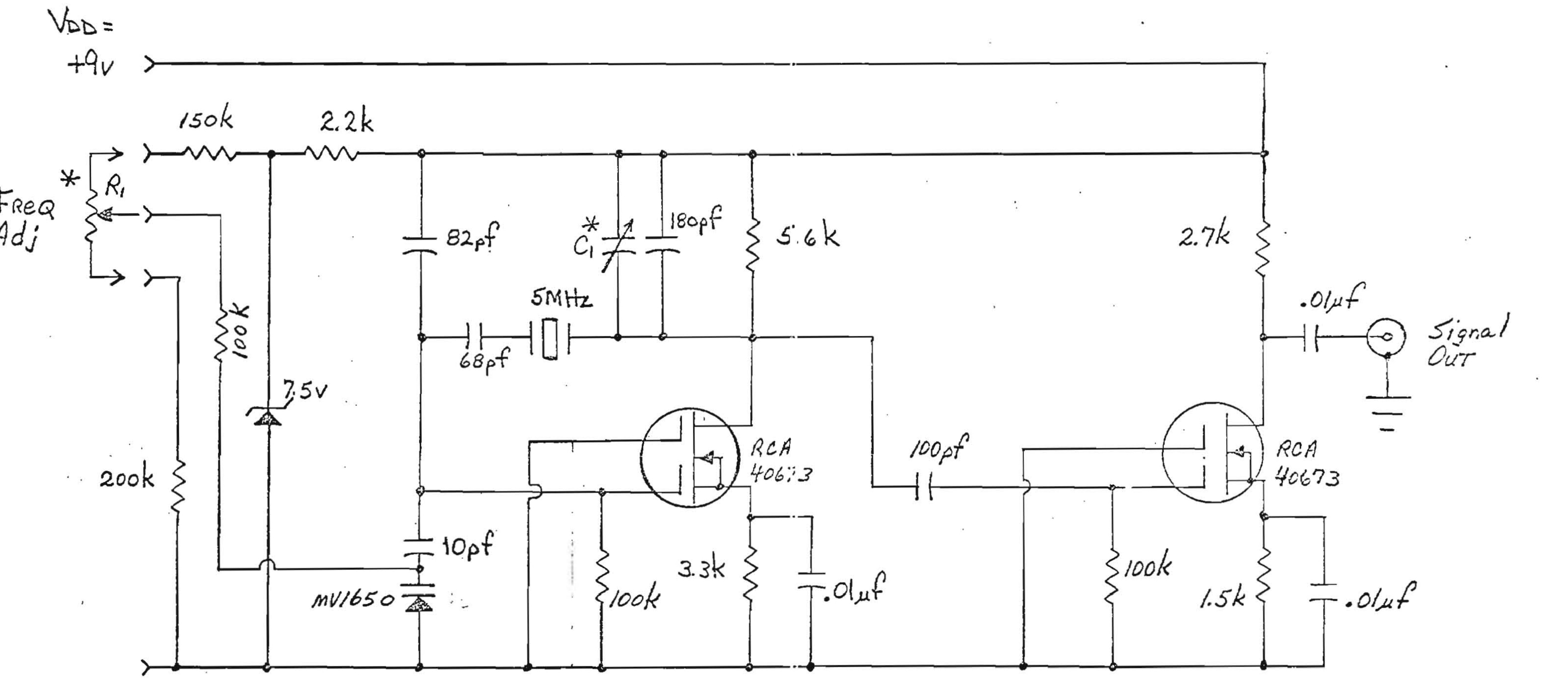
enclosure

MOSFET CRYSTAL OSCILLATOR
(Breadboard Form)

Proj. A-1344; 1/28/72

P_{IN} = 9mw
P_{XTAL} < 10µw depending on R_s
V_{OUT} ≅ 400mv p-p across 1000Ω LOAD

Freq/Voltage Stability: ~1.2×10^{-11}/mv ΔV_{DD}
Freq/Load Stability: < 1×10^{-11} for ±10% & -20° Change in Load



* R_1: 50k/25 Turn; Freq Adj of 2×10^{-8} Total end to end, ~1×10^{-10}/1/4 turn.

C_1: Motorola MMCQ101 Chip capacitor, To be added to hybrid circuit for coarse Freq. set.

Figure 1

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March 2, 1972

Commanding General, A15 APP
U. S. Army Electronics Command
ATTENTION: Solid State and Frequency Control
Division, AMSEL-KL-S
Fort Monmouth, New Jersey 07703

Contract Number: DAAB07-71-C-0301

Georgia Tech Number: A-1344

Subject: Monthly Status Report No. 5 covering the period 1 February to 29 February 1972

Dear Sir:

During this report period we have accomplished the following:

1. Built a prototype temperature control circuit in breadboard form.

2. Using the prototype model above, evaluated the frequency performance of quartz resonators during and subsequent to the warm-up from 25 to 85° C.

3. Completed the Amberlith artwork for the MOSFET oscillator using a 50:1 scale. The reduction and preparation of a 1:1 photoresist mask was by Electromask, Inc., Van Nuys, California.

4. The detailed layout of the components to be mounted on the type "D" header (base in our current oscillator design) was completed. The hole to accommodate the frequency trimming potentiometer adjusting screw was drilled through one header.

5. A stainless steel core support was designed, constructed and checked for the presence of mechanical resonances during vibration.

The temperature control circuit (block form) described in our proposal and report TR ECOM-0301 (Interim) was completed and we have commenced the performance testing of this circuit. The basic circuit is shown in Figure 1. No major circuit modifications are anticipated. The double zener regulator will be changed to a one zener configuration when the input voltage is changed to 9 V (reg.). Reference Figure 1 of Monthly Report No. 3; the operating power for 9, 10 and 11 (the temperature-sensing thermistor bridge and the following two amplifiers) should be routed to item 3 (the voltage regulator output). The control transistor and heater will still operate from unregulated power. Performance tests on the circuit are intended to establish the optimum gain for maximum temperature stability with a minimum of "hunting." A problem was found with the temperature-sensitive gain as applied to the second stage. Variations in the gain of this stage due either to changes in the value of Rfb or by the action of thermistor Rt_2

$$(G = 1 + \frac{Rfb}{Rt_2})$$

changed the operating point of the bridge, which delivers a constant error signal under steady-state conditions. The result is a slight shift in temperature and thus also in the crystal frequency. Design data and subsequent measurements have shown that this problem may be solved while maintaining the desirable features of temperature sensitive gain. Most of the performance studies were made with a 1000 ohm resistor as Rt_2.

Warm-up and stability measurements using helium-filled crystal units have shown some very important design parameters that must be taken into account. A quartz wafer in a helium-filled holder (~ 50 torr of He) is heated principally by thermal conduction through the gas from the inside of the holder cap. For experimental proof see R&D Technical Report ECOM-0440-F. The temperature that *must* be sensed and controlled is thus the *cap* temperature. The following general statements apply to the selection, physical positioning and assembly of the crystal in the HC-6 holder, the heater, the thermistor and the control transistor.

1. The heater (KAPTON-insulated foil) must be securely bonded to the walls of the holder cap using a thin layer of thermally conductive adhesive. The mylar shrink bands supplied with this type of heater were found to shrink very little and thus fail to hold the heater in good thermal contact with the holder. Other available shrink bands have questionable vacuum properties.

2. The control thermistor (Rt_1) must be located *on the cap* immediately adjacent to the heater.* When the thermistor directly senses the heater temperature, the warm-up power is removed too soon in the warm-up cycle. If the thermistor is located rather far from the heater, e.g., at the top center of the cap, the temperature over shoots before the power is reduced. Also in the latter case, the short term stability is poor due

*The ideal location for the temperature sensing thermistor is on the inside holder wall directly opposite the heater element. However, this is not a practical location at the present time.

to "hunting" of the control system.

3. The time constant (TC) of the control thermistor must be low. The thermistors investigated to date have time constants of about one second, i.e., a second is needed for the thermistor to change its temperature 63 percent of a sudden temperature shift. About five times the time constant value is required for a thermistor to change 98 percent of the temperature shift. Thin film thermistors ("Thinistors" from Victory Engineering Corp., Springfield, N. J.) having a TC of 0.075 seconds are on order.

4. The location of the control transistor *must* be on the cap--probably on the top. This component is a problem because under some conditions, it dissipates more power than the heater after warm-up. We would like to move it out of the isothermal region but we can hardly afford to waste so much power. We have not yet received the Motorola #MJC082 control transistor which was ordered in chip form. However, some measurements were made using a large, epoxy-sealed one strapped onto the heater. This latter arrangement was poor and thus most measurements were taken with the C.T. on a heat sink well away from the core assmebly.

Figure 2 illustrates the results of four experiments. The temperature range covered was 25 to 85°C. In all these experiments the crystal, heater, etc., were encased in polyurethane foam and the output data were taken from an X-Y recorder. The arrangement used to obtain the data given in Figure 2a was with both the control transistor and thermistor attached to the top of the heater and in good thermal contact with each other. The heater element was wrapped round the sides of the HC-6 cap. Figure 2b was recorded when the thermistor and heater were attached to the side of the cap, and the control transistor mounted on a separate heat sink. For Figure 2c the thermistor and heater were again attached to the side of the HC-6 cap and the control transistor remotely located. However, the heater and thermistor were in good thermal contact but not the heater and cap. For Figure 2d the thermistor was attached to the top of the cap. Both the thermistor and heater (around the side) made good contact with the cap. The control transistor was again located on a separate heat sink.

The heater power in each of these four cases was 5.4 W. The control-transistor resistance is about 4 ohm, even when saturated. This resistance was not taken into account when the heaters were ordered. However, increasing the input voltage to the heating network did not greatly chance the warm-up period. The input power usually switches from maximum (control transistor saturated) to low in about 16 seconds with 5.4 W of heater power and in about 8 seconds with 10 W of heater power. The corresponding values of initial input power during warm-up are 7.2 W and 16 W respectively. In none of these warm-up and temperature stability experiments was the heated crystal unit insulated as well as the crystal units in the final assembly are expected to be.

Final adjustments of such items as OP amplifier gain will be made under conditions that very closely approximate actual operating conditions.

As mentioned earlier the master artwork and photoresist exposure mask for the oscillator are now ready. A photograph of the mask is shown in Figure 3. The mask is a negative of the Cr + Au conductor pattern to be developed on the thin (0.015 in.) alumina substrates. Subsequent component bonding will be by soldering. Active elements will be die bonded when possible and connected into the circuit with flying leads.

The items to be located on the type "D" header (base), and thus not under temperature control, could only be determined after the oscillator and temperature controller were built and evaluated. Figure 4 is a floor plan of the header showing the placement of the voltage regulator in a type TO-5 can, and the frequency trimming potentiometer (Trimpot) housing. This housing consists of a HC-6/U cap spot-welded top down to the base. Flying leads attached to the potentiometer will be connected to the pins of a 3-pin header before it is soldered in place. A 0.094 in. hole through the base and Trimpot housing will provide access to the adjustment screw. Note that the interior of the Trimpot housing is not evacuated, thus the vacuum compatability of the Trimpot is not a design factor.

The stainless steel pedestal which positions the crystal and associated circuitry in the isothermal region is also shown in Figure 4. The location of the Trimpot on the header is justified since the voltage applied to the varicap (MV 1650) is not dependent on the end-to-end value of Trimpot resistance but on the ratio of the resistances on each side of the slider. The voltage regulator (μA 723) has a temperature coefficient of voltage of .002%/°C. When ΔT is 115°C (-40 to +75°C) the voltage change (ΔV) is 0.230 percent. The total ΔV would then be 20.7 mV for a 9 V regulated output voltage. The MOSFET oscillator has a measured frequency versus voltage stability of 1.2×10^{-11}/mV. The above value of total ΔV would thus not affect the frequency/temperature stability requirement of $\pm 1 \times 10^{-8}$ over the specified temperature range. The temperature control circuitry is not as critically dependent on supply voltage variations as the oscillator. In addition, both the oscillator and temperature controller have temperature stabilized zener diodes as part of the input voltage circuit.

The core support method has been a small problem. We have at present settled for a stainless steel "pedestal" of the design shown in Figure 5. The pedestal will be spot-welded to the center of the base and to the crystal holder at the top. The R.F. output lead will be routed through its hollow interior, a necessary factor for the reduction of frequency/load variations. The S.S. pedestal under the worst-case situation (ΔT = 125°C) will conduct about 250 mW of heat. Before the 0.040 inch center hole was drilled the heat flow was 315 mW (calculated). The actual heat will be lower than calculated value by an amount dependent upon the heat transfer at the upper and lower spot-welds. If the heat flow is intolerable, we can make the pedestal of VESPEL, a polyimide having good mechanical and electrical properties plus exceptional vacuum compatibility. The K value for VESPEL is about 3.5 X 10^{-3} as compared to 160 X 10^{-3} for stainless steel. However, as VESPEL is an insulator, an additional electrical would have to be run from the base to components in the isothermal zone. We are presently using the stainless steel pedestal as the ground connection.

Work for the next period will include:

1. Complete the MOSFET oscillator in microcircuit form and evaluate its performance. The zener diodes are the only components not on hand. The crystal units were finally ordered from Bulova after CTS Knights raised the price to $150.00 each.

2. Complete the master artwork and prepare the photoresist mask for the temperature control circuit.

3. Procurement of certain key items continues to be a problem. We are working closely with the Supply Services group at Georgia Tech in order to expedite the delivery of these items.

Respectfully submitted,

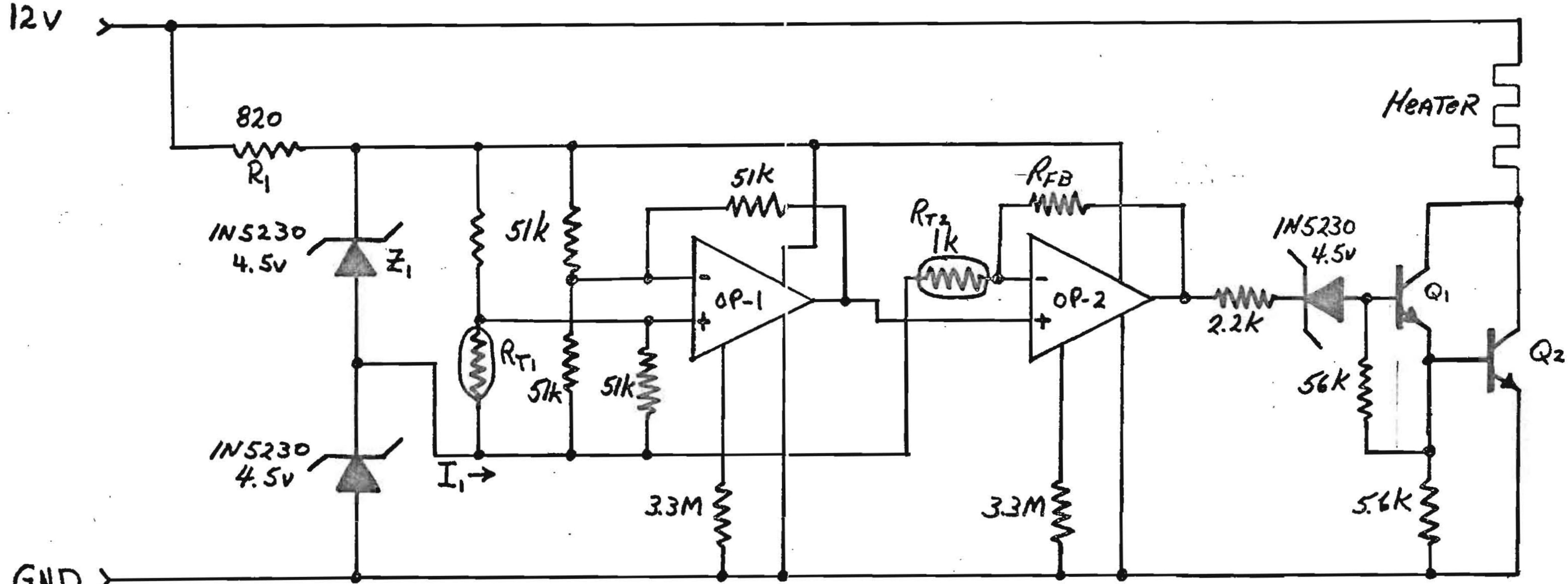
Raymond K. Hart
Project Director

RKH:cc

FIG. I: PROPORTIONAL TEMPERATURE CONTROLLER

A-1344
2/28/72

Breadboard

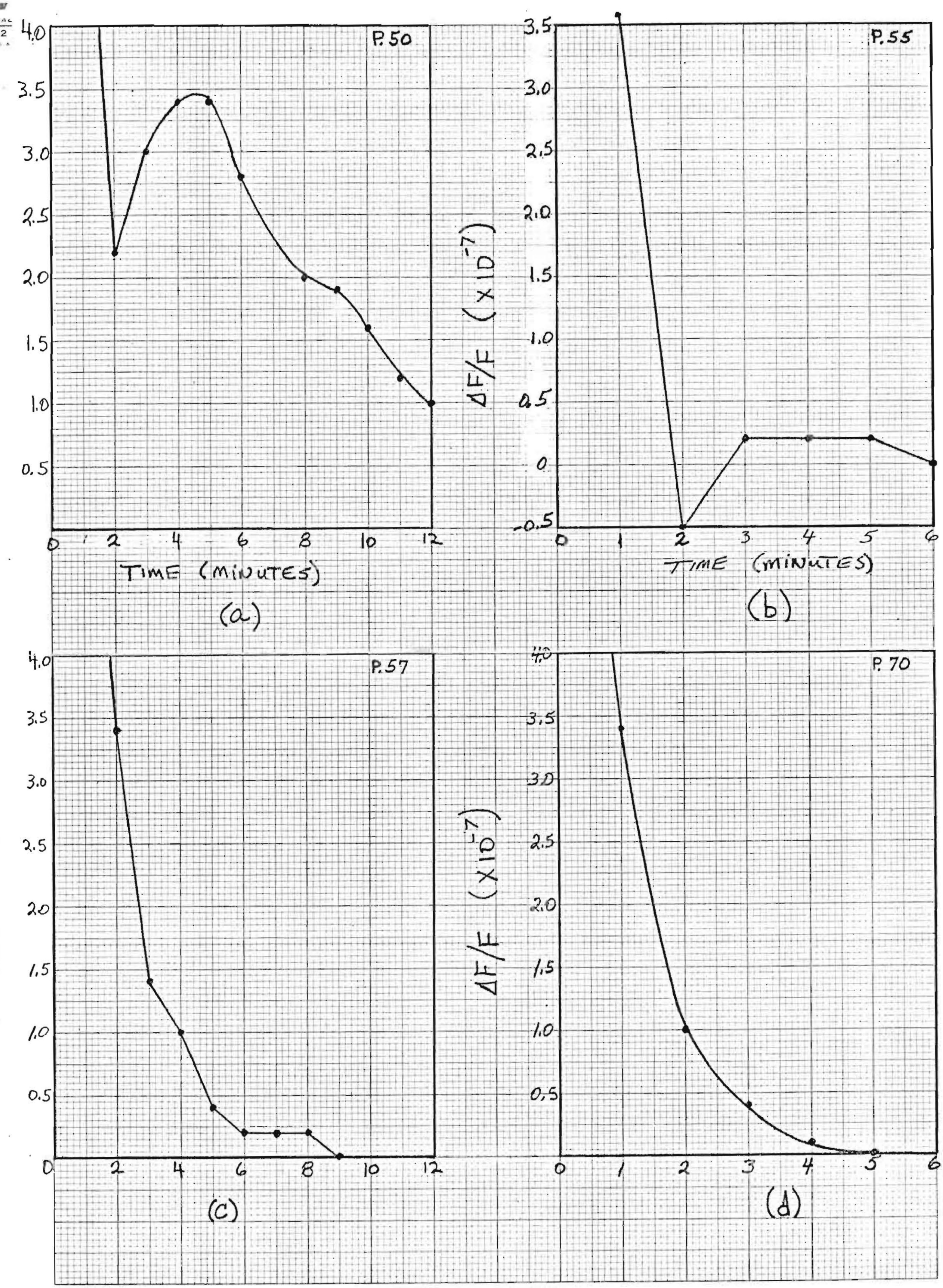


OP-1, OP-2 : FAIRCHILD μA776
Q_1 : 2N2222
Q_2 : MOTOROLA MJE 521

R_{FB} : Selected
R_{T1} : 500kΩ @ Room Temp (Bead)

I_1 = 130μa during warm-up
57μa after warm-up

Changes to be made in hybrid model:
(1) R_1 & Z_1 Replaced with a single resistor.
(2) Zeners will be Motorola MZC 4.7B5
(3) Q_2 will be Motorola MJC 082
(4) R_{T1} will be Veco Thinistor (Thin-Film Thermistor)



quares to the Inch

Figure 2

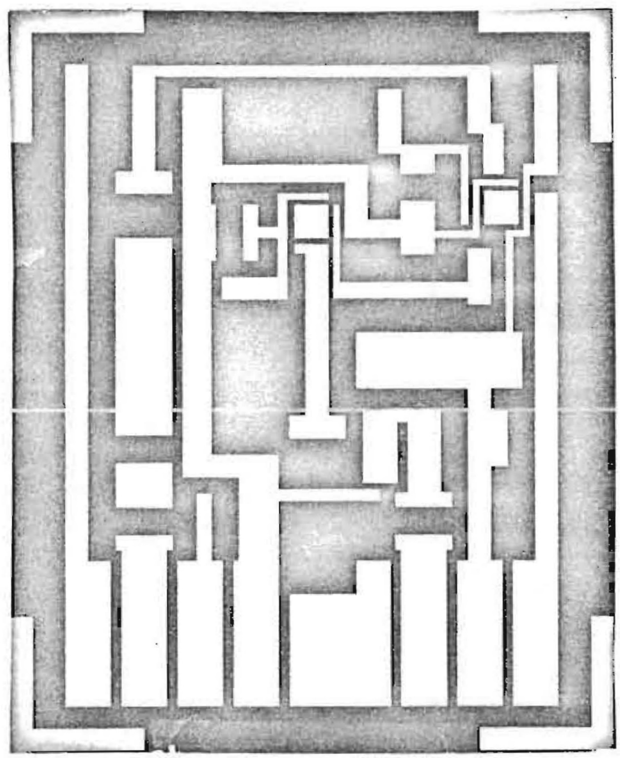


Figure 3. Photoresist Exposure Mask for MOSFET Oscillator. White Portions are Cr + Au Conductors. Scale: 6X.

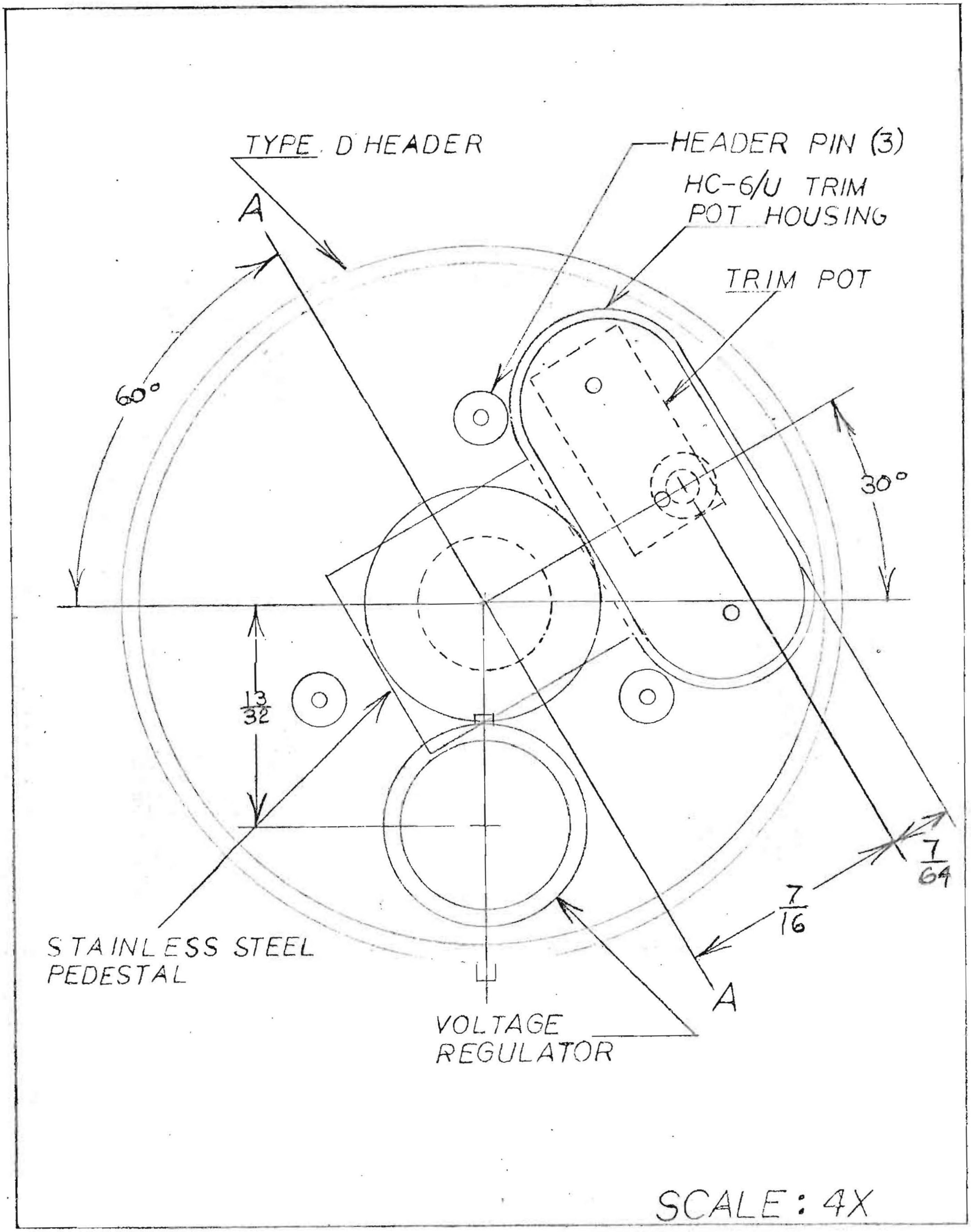


Figure 4. "Floor Plan" for the Type "D" Base. Crystal Holder on the S.S. Pedestal Positioned so the Pins are on Line A-A.

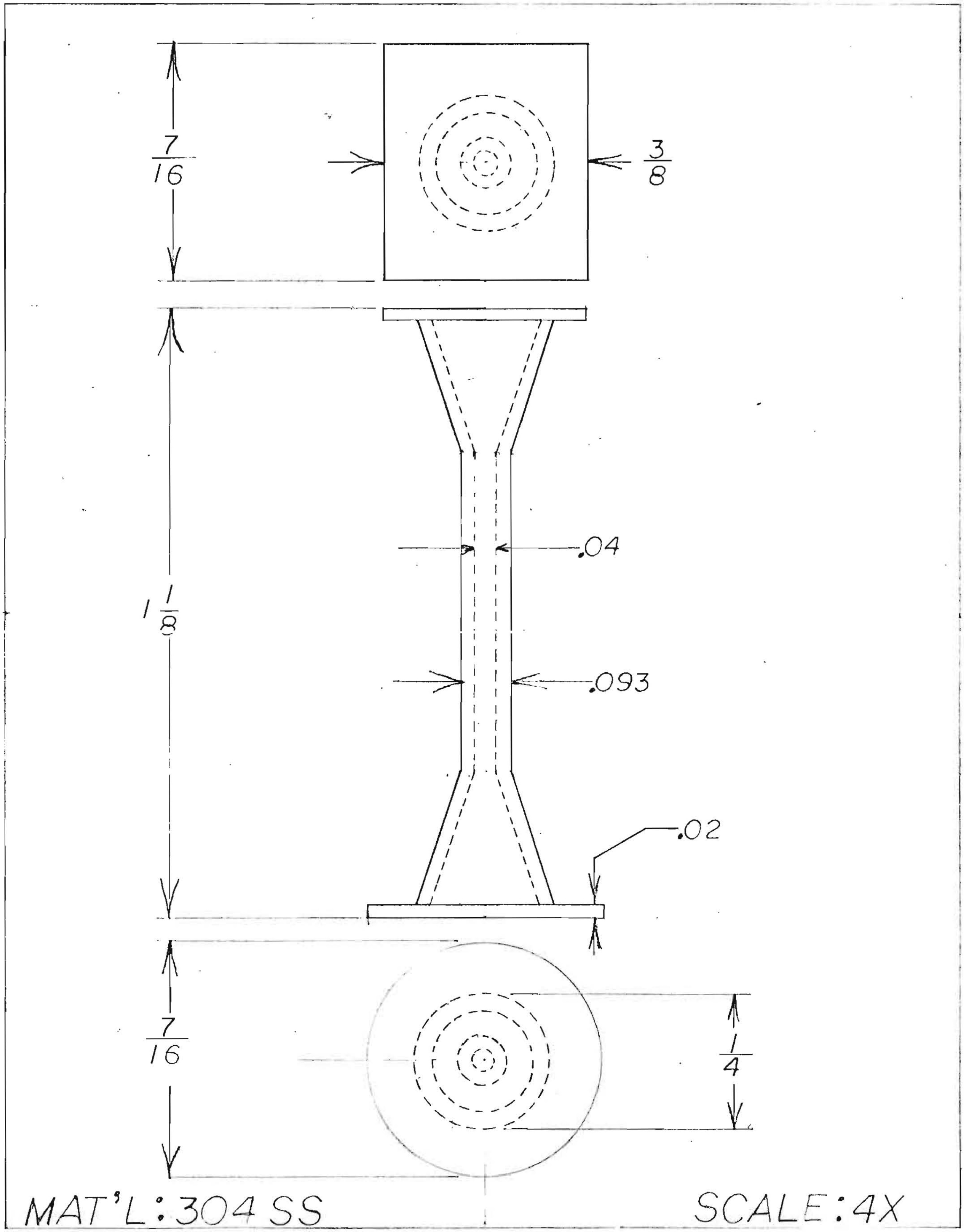


Figure 5. Stainless Steel Core-Support Pedestal. Lower (Round) End Spot-Welds to Type "D" Base. Upper (Rectangular) End Spot-Welds to HC-6 Holder Flange.

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March 30, 1972

Commanding General, A15 AAP
U. S. Army Electronics Command
ATTENTION: Solid State and Frequency Control
Division, AMSEL-KL-S
Fort Monmouth, New Jersey 07703

Contract Number: DAAB07-71-C-0301

Georgia Tech Number: A-1344

Subject: Monthly Status Report No. 6 covering the period 1 March to 31 March 1972

Dear Sir:

During this report we have accomplished the following:

1. Further investigation into the parameters of the thermal system.

2. Completion of the artwork for the remaining photomasks.

3. Assembled and tested voltage regulator.

4. Began construction of the cold-weld base sub-assembly.

5. Constructed and leak tested a modified type-D cold-weld cap.

6. Began construction of the hybrid oscillator.

In Letter Report No. 5 we showed how the placement and thermal contact of the thermistor and heater with respect to the can affects the warm-up characteristics of the quartz crystal. In those experiments the effects of the two side mounted alumina circuit boards was not considered. Figure 1 shows two warm-up curves in which all variables were kept constant except thermal loading due to the alumina circuit boards. The thermistor was bonded to the top edge of the crystal can and the whole crystal-heater-thermistor assembly was encased in polyurethane foam. Other system parameters are indicated on the graph. The frequency was measured at one minute intervals beginning one minute after turn on. Thus, the plots do not indicate the overshoot and undershoot which occurred during the first minute. The added mass of the alumina circuit boards decreased the degree of overshoot/undershoot of the system and the frequency offset at one minute was improved by a factor of two. Thus, it appears desirable to have as much thermal mass in the system as can be heated to the operating temperature in the allowable time of one minute. The larger thermal capacity will also aid the short-term temperature stability. Note that after the first minute the frequency offset in each case is not significantly different.

In Fig. 2 the family of curves show the effect of system gain on the warm-up characteristics. All other variables, such as power input and thermal insulation were held constant during this experiment. The frequency offset after one minute shows an increase in a positive direction with an increased system gain. At the higher gains the system bandwidth becomes smaller and the full power input remains on longer. The temperature overshoot is thus high and the power is reduced to almost zero. The temperature falls rapidly and full power is applied again for a shorter period of time. This combination of power input and system gain results in a temperature stabilization period which is longer than desired. At the lower gains the bandwidth is too large and the heater power is reduced too soon. The temperature drops rapidly and is still low at the end of one minute. At gains between approximately 60 and 200 the frequency offset is within $\pm$ 1 X 10^{-7} of the reference frequency after one minute from turn-on. In this range of system gain the power input is reduced at a rate which minimizes the temperature overshoot and undershoot. Notice how the differences between the curves at two minutes through ten minutes becomes less, indicating very little dependence on the gain of the system. To understand this process better, another experiment was performed and the results are shown in Fig. 3. Here the system gain was held constant at about 200 and the effect of adding thermal insulation to the thermistor was investigated. The thermal insulation consisted of a small block of polyurethane foam cemented directly on top of the thermistor. The frequency offset after one minute was essentially unchanged after adding the insulation, verifying its dependency on power input and system gain, assuming a constant value of heater thermal insulation (air in this case). After two minutes, the frequency offset could be reduced 30 percent by reducing the thermistor heat loss and correspondingly reduce the system power. Bonding a thin-film thermistor to the can with a good thermally conductive epoxy, such as Delta-Bond 152, should lower the frequency offset still further. In addition, the final assembly will be sealed in vacuum and surrounded with NRC insulation. The convection and radiation losses will therefore be virtually nonexistent and the thermistor will sense the temperature of the can and not the surrounding environment. Data shown in Fig. 4 was obtained under similar conditions to that shown in Fig. 2, except the thermistor was insulated in polyurethane foam. Note scale change for $\Delta F/F$ in Fig. 4. This figure indicates that with a gain of around 100 the frequency offset requirement is met at one minute. With the additional thermal insulation and improved thermal contact of heater, thermistor, and crystal can in the final model the frequency offset requirements at two, four and fifteen minutes should be met.

The last letter report stated the problem encountered with transistor Q_2 (control transistor) of the temperature control circuit. All of the warm-up data in this report were taken with this transistor located outside the isothermal region. The chip form of this component has been received. It will be mounted on a beryllium oxide pad which in turn will be attached to the top of the crystal can adjacent to the thermistor, using Delta-Bond 152 epoxy. Flying leads will interconnect the transistor to the temperature circuit board. It is believed that this arrangement will allow for rapid heat transfer between the control transistor and the crystal can during the period when the control transistor becomes the major source of heat.

The artwork for the temperature circuit board has been completed and sent to Electromask, Inc., for reduction. The simple photomask for the beryllium oxide mounting pad was produced in-house.

The voltage regulator was assembled and tested during this report period. The circuit diagram is shown in Fig. 5. The change in the output voltage with an input voltage change of ± 5 percent is less than 1 mV. Fig. 6 shows a typical T.C. of output voltage obtained before final assembly of the regulator components. The μA723 regulator is packaged in a type TO-5 can. The remainder of the components are soldered directly to the regulator leads and rest on the base. Eighth watt resistors are used and all components are potted to the TO-5 base in this sub-assembly with silicon rubber. Only the input, output, and ground leads are carried through the potting. This sub-assembly will also be attached to the type-D base of the main unit with Delta-Bond epoxy, which has good vacuum characteristics as well as good thermal conductivity.

Work on the modified type-D package has been delayed due to procurement problems of the necessary materials. The frequency control potentiometer has been mounted on the base but has not been vacuum sealed. The potentiometer is mounted inside a modified HC-6 holder with a three terminal base. This HC-6 holder is mounted upside down on the type-D base so that the adjustment screw is aligned with the hole drilled through the type-D base and is spot-weld in place. Epoxy will be used to provide a vacuum seal between the HC-6 holder and the type-D base. The type-D cap has been extended in length to 3" by cutting the cap in half and sweating in an extension with pure tin. A fabricated cap has been leak tested in the 10^{-6} torr aange and appears to be suitable for the present application.

All the parts necessary to build the oscillator have now been received and fabrication was begun during the last week of March. Much of this time was spent getting tooled-up to do the necessary bonding. The oscillator should be completed during the next report period and will receive extensive exposure in the next letter report.

In addition, work for the next period will include:

1. Fabricate the temperature control microcircuit. The op-amps and zener diodes for this circuit are not yet on hand, neither is the photomask.

2. Complete the base assembly including mounting the crystal and heater.

3. Carry out independent aging studies and warm-up experiments on the crystal units.

4. Mounting the circuit boards to the crystal holder and performing pre-seal warm-up and frequency stability tests.

5. Check for mechanical resonances in the mounting system and vibration resistance of all bonds.

Respectfully submitted,

Raymond K. Hart
Project Director

RKH:cc

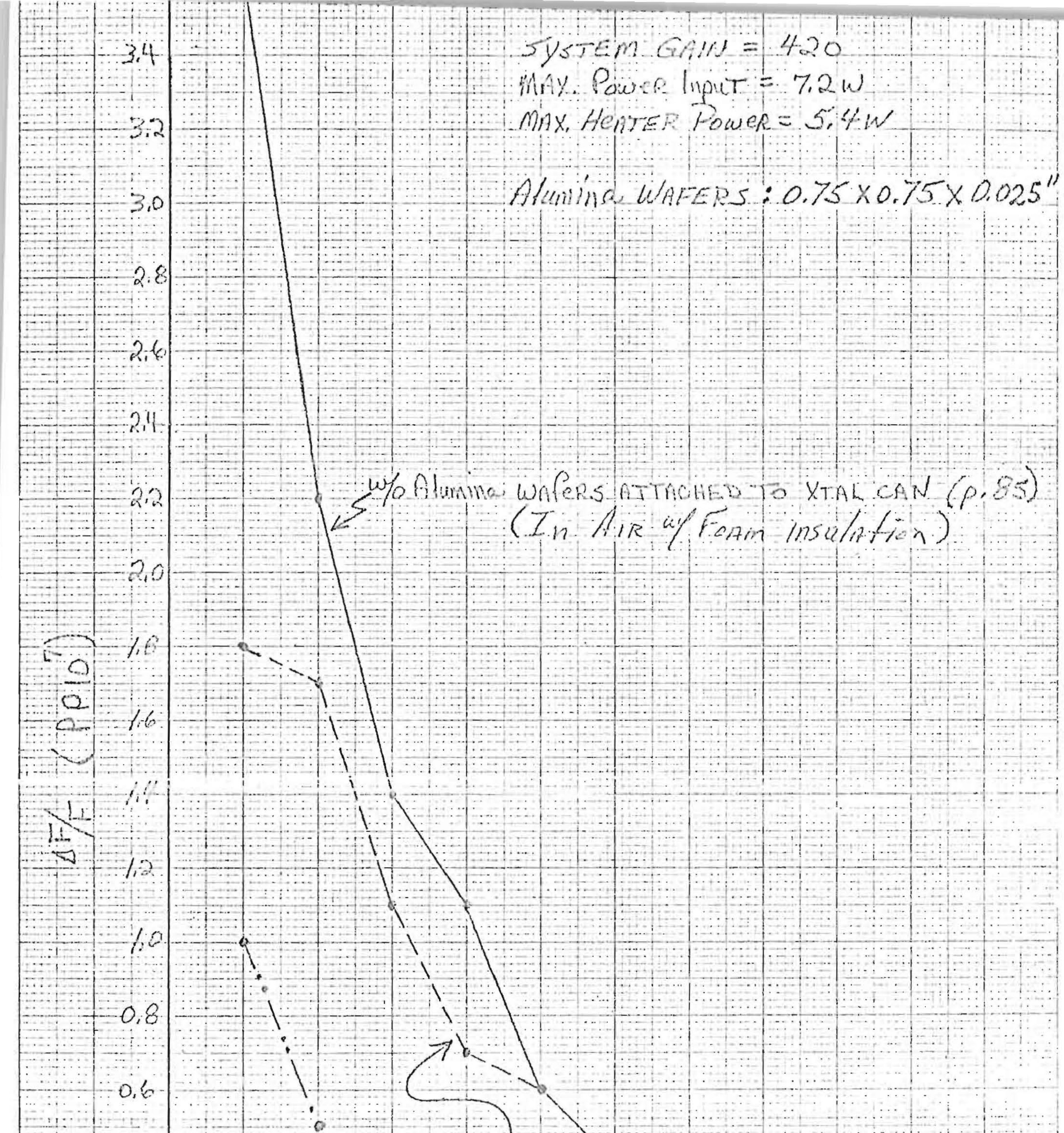
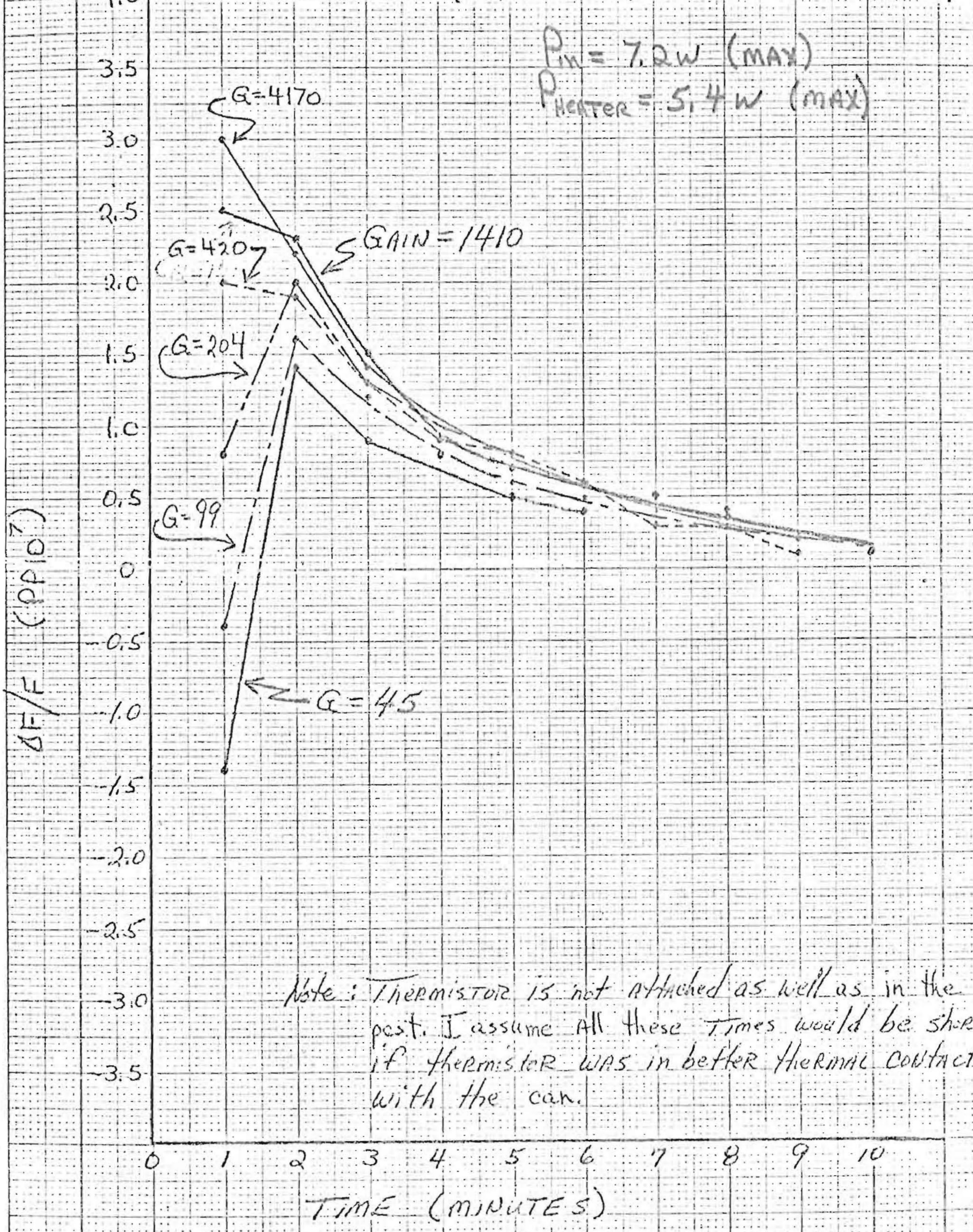


FIG 1: Effect ON WARM-UP of Adding Alumina Circuit Boards To Sides of CRYSTAL CAN.

FIG. 2: Effect on Warm-Up of Gain Variation

All other parameters held constant (p. 82-83)

Alumina wafers (.75 x .75 x .025") attached to sides of cap.



Note: Thermistor is not attached as well as in the past. I assume all these times would be shorter if thermistor was in better thermal contact with the can.

FIG. 3: Effect on Warm-Up of Thermistor Insulation

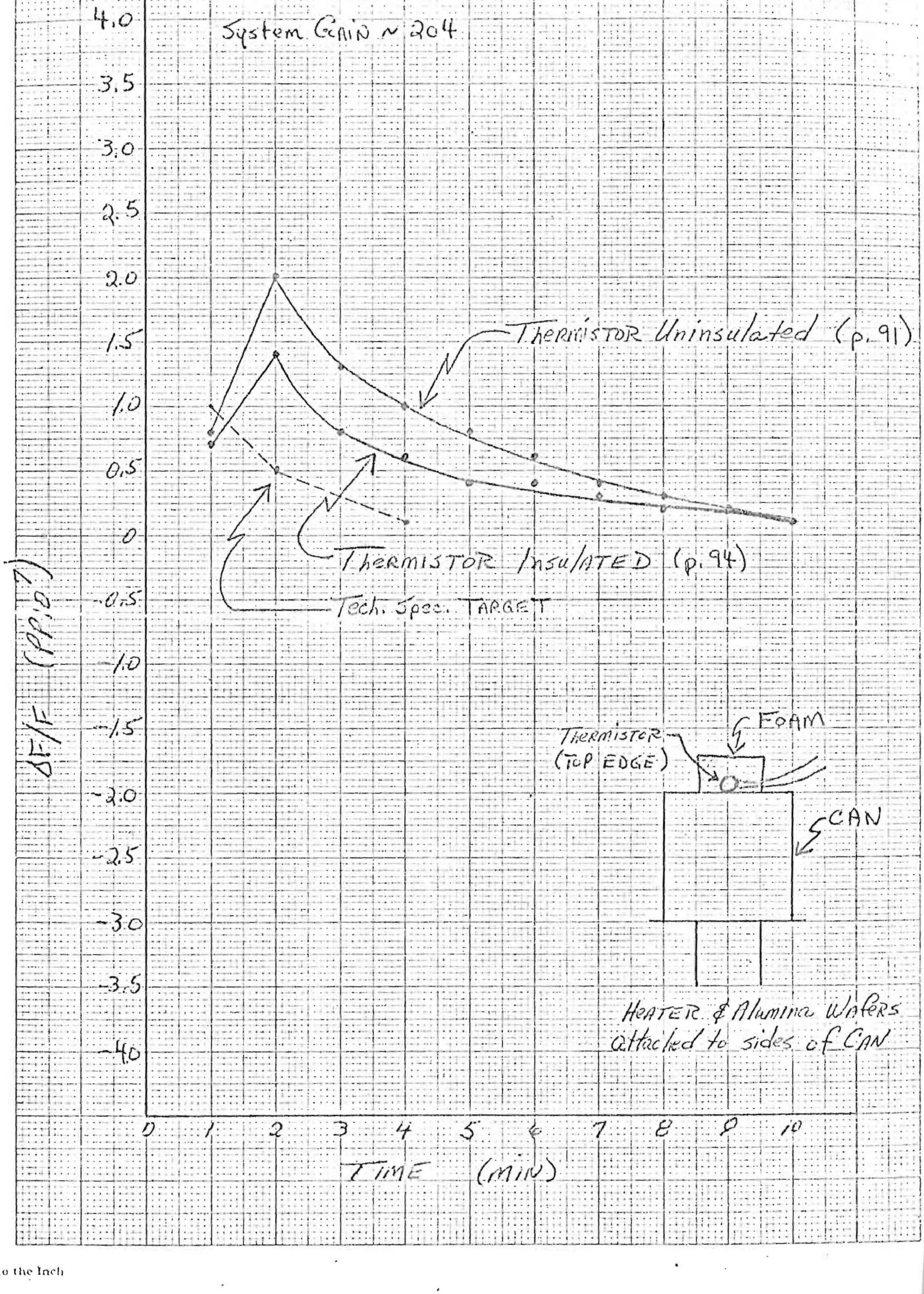


FIG. 4: Effect of Gain Variation on Warm-up with thermistor Insulated.

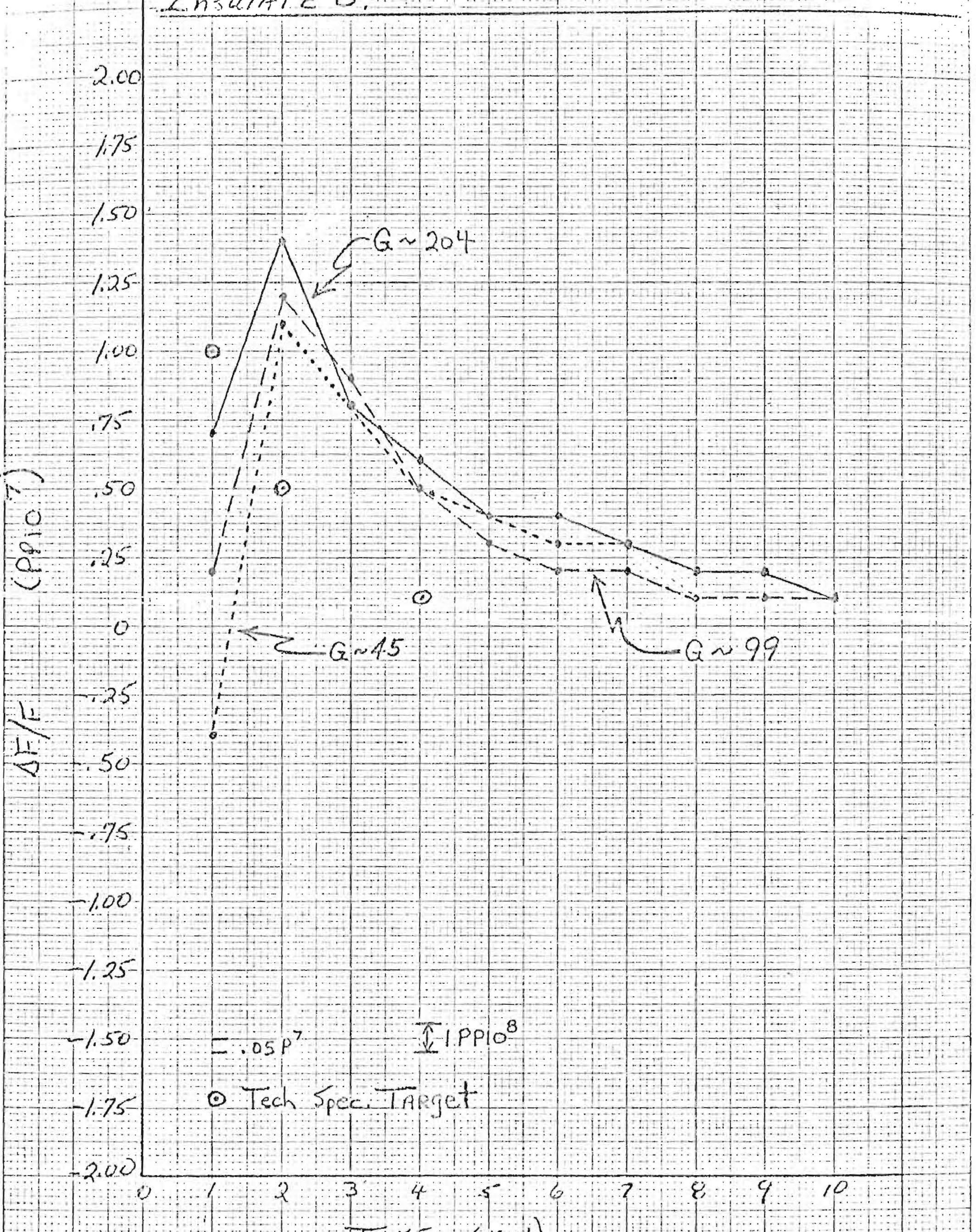
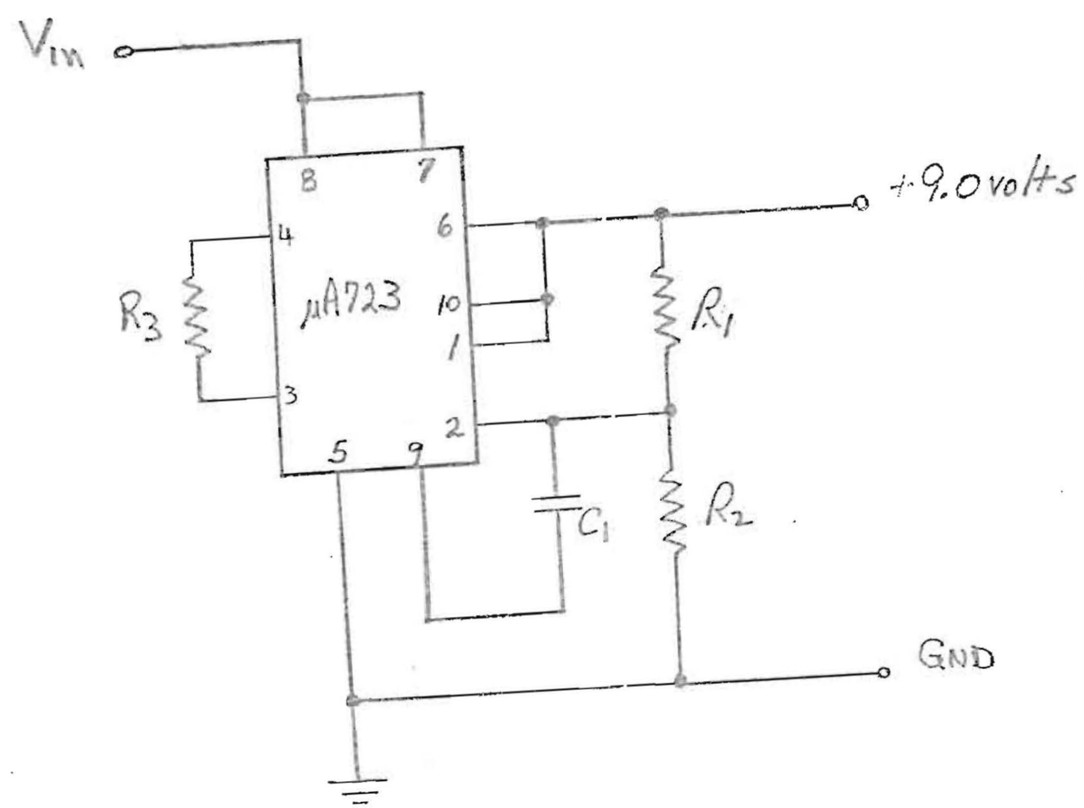


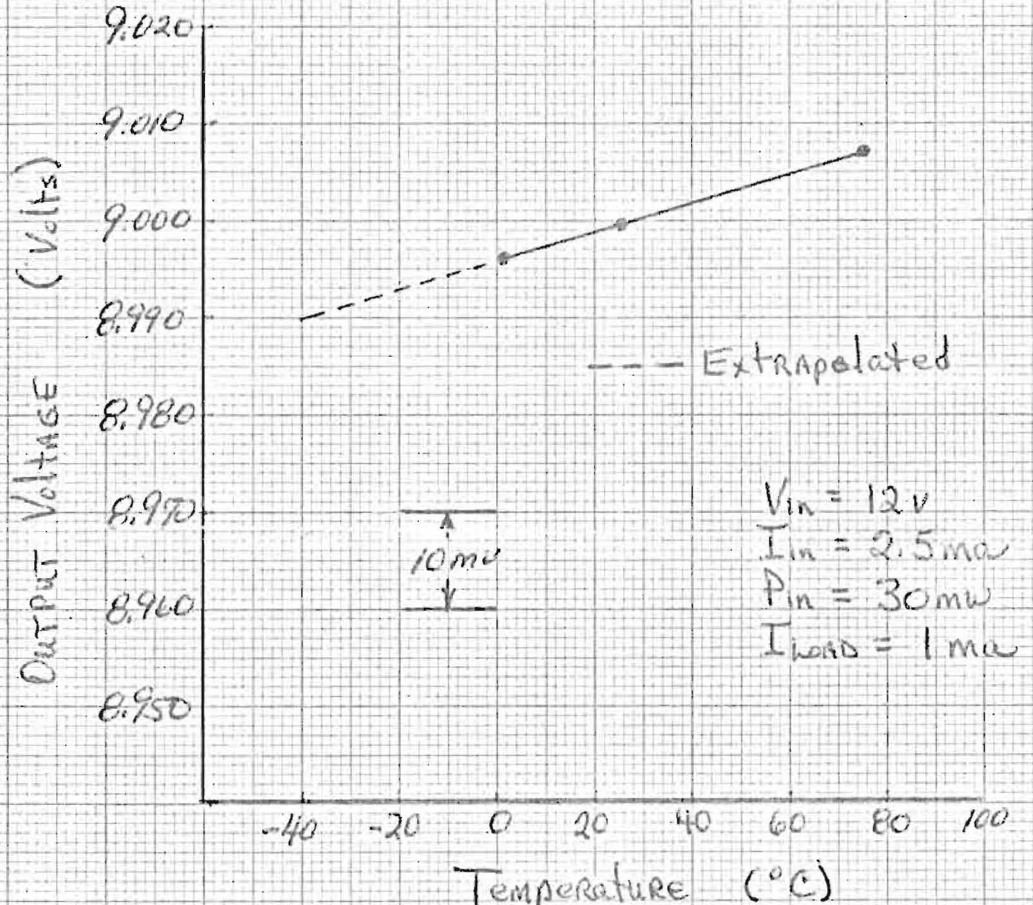
FIGURE 5: VOLTAGE REGULATOR



R_1 : 1.5kΩ / 1/8 w
R_2 : 6.8kΩ / 1/8 w
R_3 : 1.5kΩ / 1/8 w
C_1 : 100 pf
V_{in} : 12v ± 5%

At 12v input and load current of 1ma the power input is 30mw.

FIGURE 6: Regulator Voltage vs Temperature



ΔV_{OUT} from +1°C to 75°C = 11mv
Expected ΔV_{OUT} from −40°C to +75°C = 16.5mv

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May 3, 1972

Commanding General, A15 AAP
U. S. Army Electronics Command
ATTENTION: Solid State and Frequency Control
Division, AMSEL-KL-S
Fort Monmouth, New Jersey 07703

Contract Number: DAAB07-71-C-0301

Georgia Tech Number: A-1344

Subject: Monthly Status Report No. 7 Covering the Period 1 April to 30 April 1972

Dear Sir:

Progress during the period is summarized as follows:

1. Fabrication of the hybrid oscillator microcircuit was continued and is near completion.

2. Commenced fabrication of the hybrid temperature control circuit.

3. Construction of the base assembly was completed, except for mounting of the crystal unit.

4. Conducted independent aging studies on the crystal units.

Figure 1 is a photograph of one of the hybrid oscillator circuits assembled during the period and Fig. 2 is the circuit diagram. Film conductors are gold over chromium. The gold film consists of 5000 A of evaporated gold plus 3 microns of electroplated gold. A thin layer (≃ 1000 A) of chromium was evaporated to enhance adherence of the gold to the alumina substrate. The film was post annealed at 500 °C for 15 minutes and then slowly cooled. Annealing of the electroplated gold enhanced the ability to make thermal compression wire bonds to the gold film. The conductor pattern was formed by conventional photolithographic techniques. The resistors and capacitors were obtained with pre-tinned terminations and soldered to the gold film by reflow techniques, except, for R_3. Through error, film terminations for soldering R_3 were omitted in the conductor pattern. Rather than remake the artwork and delay fabrication, R_3 was epoxied to the substrate and connected to the conductors with flying gold leads. Diodes D_1 and D_2 and adjustable capacitor C_d were obtained as silicon chips and secured to the substrate by die bonding to the conductors for one termination. Flying gold leads were bonded by thermal compression techniques (T.C.) to make connection from the aluminum pads on the chips to the conductor pattern. RCA does not supply the MOSFETS Q_1 and Q_2 in chip form. The MOSFET chips were dismantled with leads intact from their TO-72 cans and epoxied to the substrate. Some difficulty was experienced with bonding the aluminum leads of the MOSFETS to the gold film as discussed subsequently.

Two oscillator circuits were fabricated using solder reflow to attach the resistors and capacitors. Flux was required to obtain a good bond to the gold film. The soldering has two disadvantages. Occasionally, too much tin-lead solder diffuses into the gold resulting in undesirable leaching of the gold film. Secondly, complete removal of the flux residue is near impossible by the limited cleaning technique available after the components are mounted. It is feared that the flux residue will result in undesirable outgassing in the final package.

A third circuit was fabricated using conductive epoxy to terminate the resistors and capacitors to the gold film. From a standpoint of ease of fabrication, the epoxy has proven to be more desirable than soldering. Current plans are to use this circuit in final assembly.

Considerable care must be taken in dismantling the MOSFETS from their containers. They are easily damaged and several were damaged in the process of dismantling. Reliable bonds of the aluminum leads of the MOSFETS to the gold film conductors could not be made by T.C. or ultrasonic bonding. The problem appears to be the roughness of the gold surface on the alumina substrate. Such bonds were readily made on gold films deposited on polished quartz and glass surfaces. To obtain reliable bonds, the aluminum leads were positioned and tacked to the gold film with a T.C. wedge bonder, then secured with conductive epoxy.

The hybrid oscillator has been bench tested at room temperature. Performance was as good as the breadboard model in similar tests. However, some component values required changing. Values of C_b and C_c were changed to 100 pF and 56 pF, respectively. This was done to adjust the feedback to gate 1. The value of R_6 was changed from 2.7 kΩ to 4.7 kΩ in order to increase the gain of the buffer stage. Apparently, the gain of the MOSFETS decreased after their removal from the TO-72 packages. Also, the difference in stray capacitances in the breadboard and microcircuit forms may have contributed to the required changes of component values.

Photoengraving of the conductor pattern for the hybrid temperature control circuit was completed. The operational amplifiers have not been received, and this has delayed completion of the circuit. Delivery of the amplifiers is expected soon.

Figure 3 is a photograph of the base assembly. The assembly is complete for the first model, except, for mounting of the crystal unit. The base was leak tested to the 10^{-6} torr range and appears satisfactory. Figure 4 shows the can fabricated by cutting a type-D cold-weld cap in half and soldering the flange and top pieces to an extension section. Fabrication of these items were discussed on page 3 of report number 6.

Aging studies on the crystal units have been conducted for a period of two weeks. Figures 5 and 6 are graphs of the frequency change versus the time in days at 85 °C for five crystal units. Unit 6 is planned for inclusion in the final assembly of the first model. Warm-up studies are in progress and will be detailed in the next report.

Testing and fabrication of the oscillator and temperature control circuits are scheduled for completion during the next period. In addition, mounting of the microcircuit boards to the crystal holder, performing pre-seal warm-up and frequency stability tests, and examination for mechanical resonance and vibration resistance is expected to be completed.

Respectfully submitted,

Raymond K. Hart
Project Director

RKH/jl

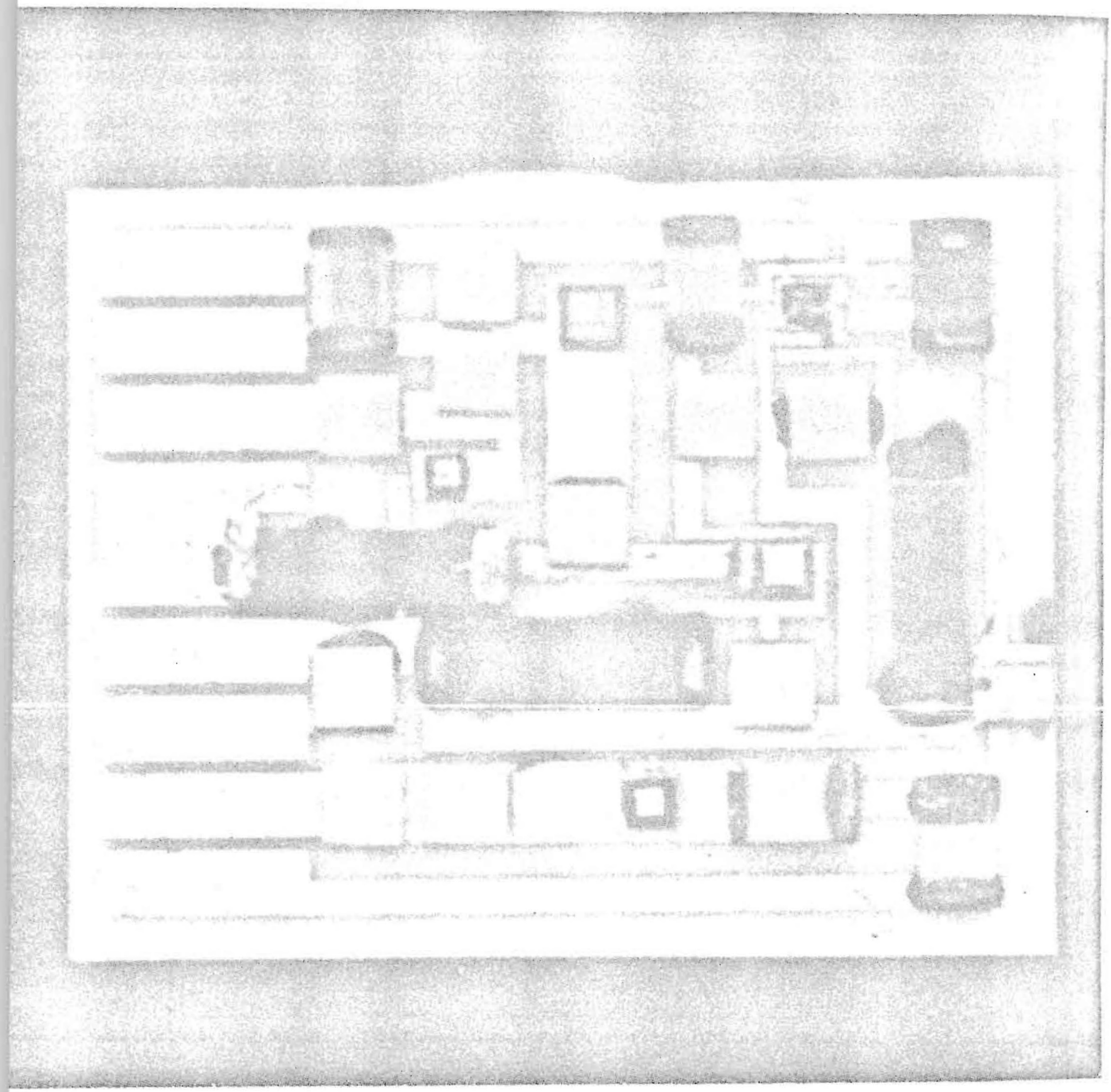
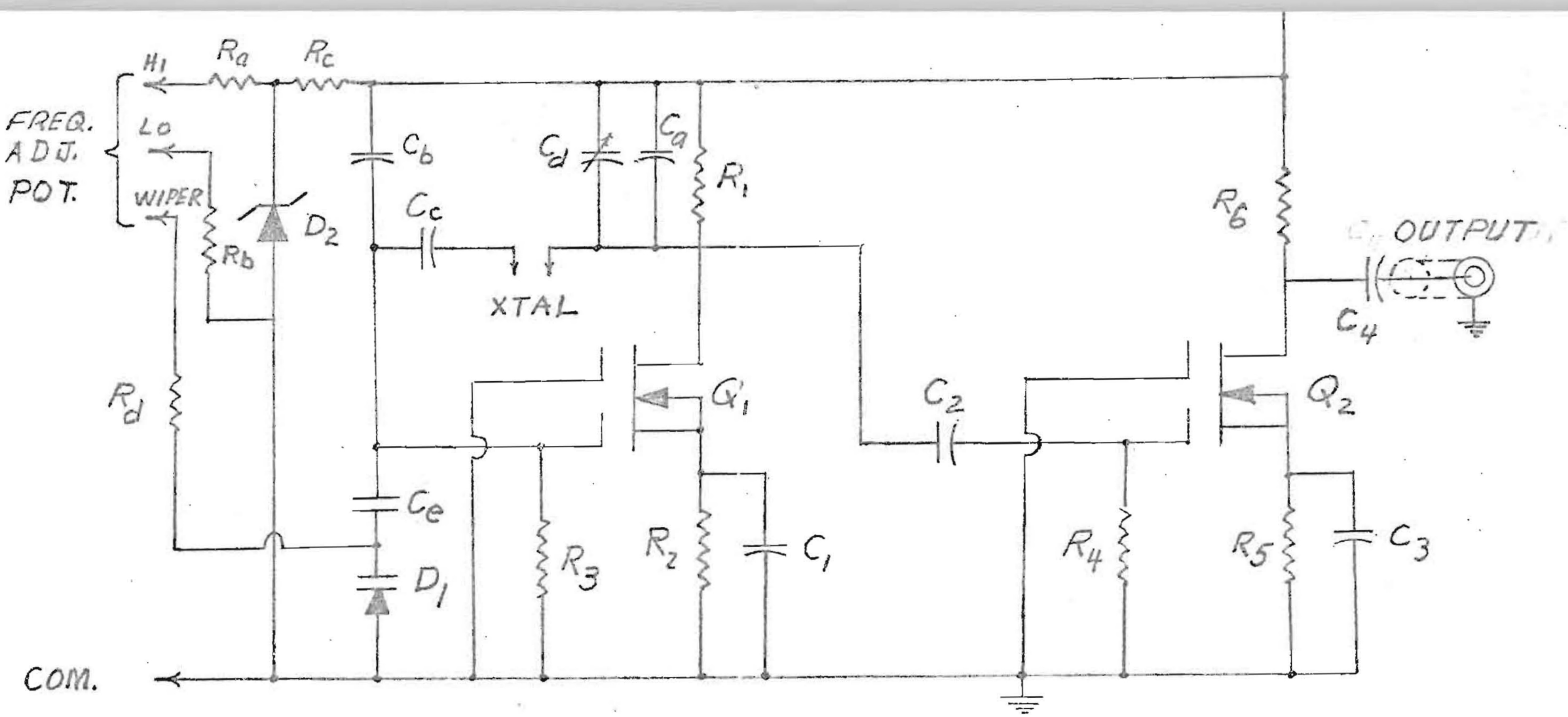


Fig. 1. Hybrid Oscillator Circuit



I_{DS} $Q_1 = 300\,\mu A$
I_{DS} $Q_2 = 550\,\mu A$
XTAL P: 1-10 μW, depending on R_s
$V_{OUT} \gtrsim$ 400 mV p-p ACROSS 1000 Ω LOAD

COMPONENT LIST:

Q_1 & Q_2	-	MOSFET, RCA # 40673
D_1	-	Var. Cap. diode, MSI Electronics # 3800
D_2	-	Zener diode, Motorola # MZC6.8B1
Cd	-	1-31 pF, Motorola # MMCQ 101-1

COMPONENT LIST CONTINUED:

C_1, C_3, C_4	-	.01 μF ± 20%
C_2	-	100 pF ± 10%
Ca	-	180 pF ± 1%
Cb	-	100 pF ± 1%
Cc	-	56 pF ± 1%
Ce	-	8.2 pF ± 1%

R_1	-	5.6 kΩ
R_2	-	3.3 kΩ
R_3, R_4	-	100 kΩ
R_5	-	1.5 kΩ
R_6	-	4.7 kΩ
Rc	-	22 kΩ
Ra	-	150 kΩ
Rb	-	200 kΩ
Rd	-	100 kΩ

$\left.\begin{matrix} Ra \\ Rb \\ Rd \end{matrix}\right\}$ Final values will be selected during final frequency adjustment

FIGURE 2

MOSFET CRYSTAL OSCILLATOR

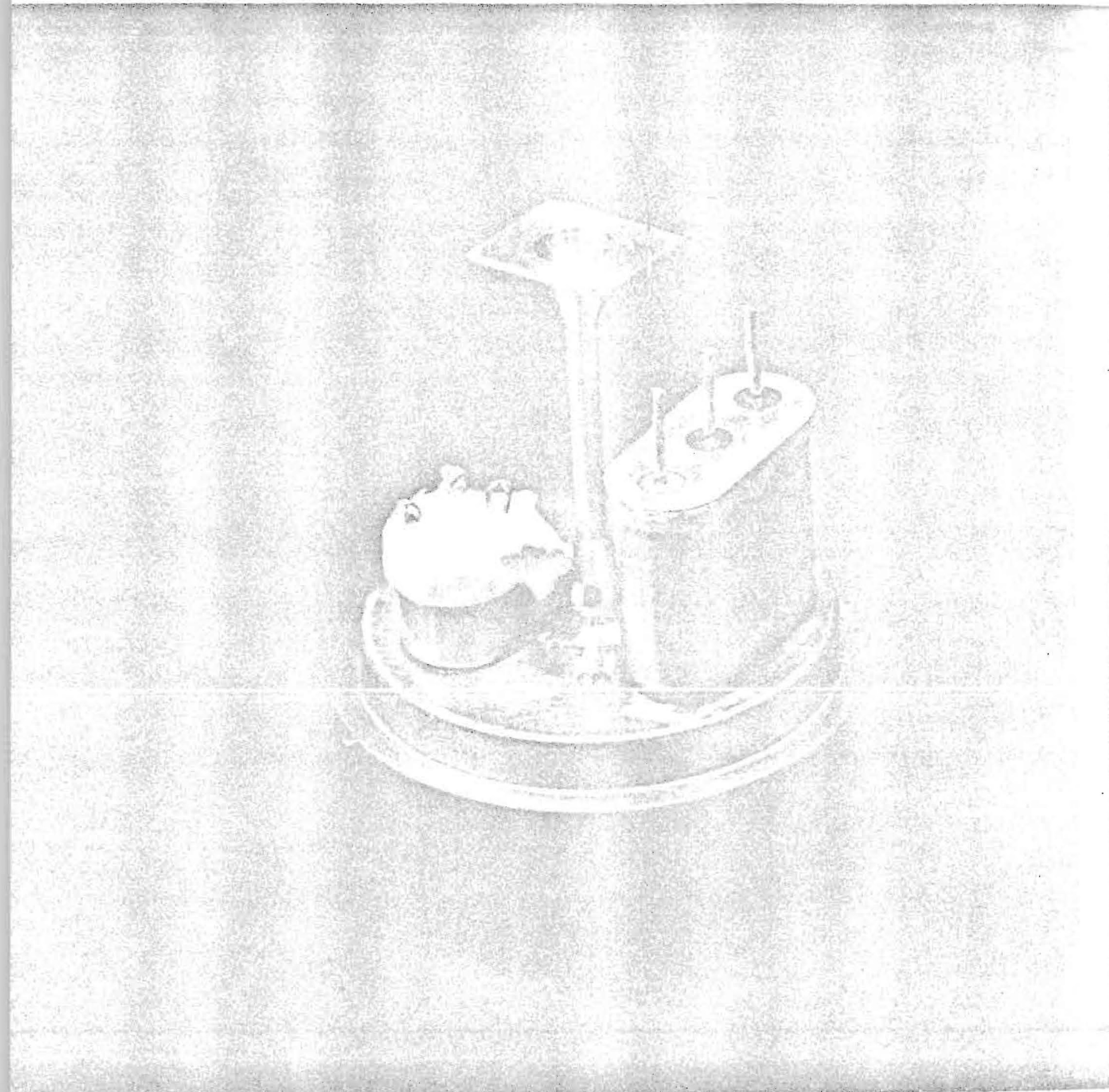


Fig. 3. Photograph of Base Assembly

Fig. 4. Photograph of Extended Type-D Cap

A - Type-D cap
B - Top of cap after cutting
C - Flange half of cap after cutting
D - Tube extension
E - B & C soldered to extension

FIGURE 5: AGING OF CRYSTAL RESONATORS NOS. 2 AND 3

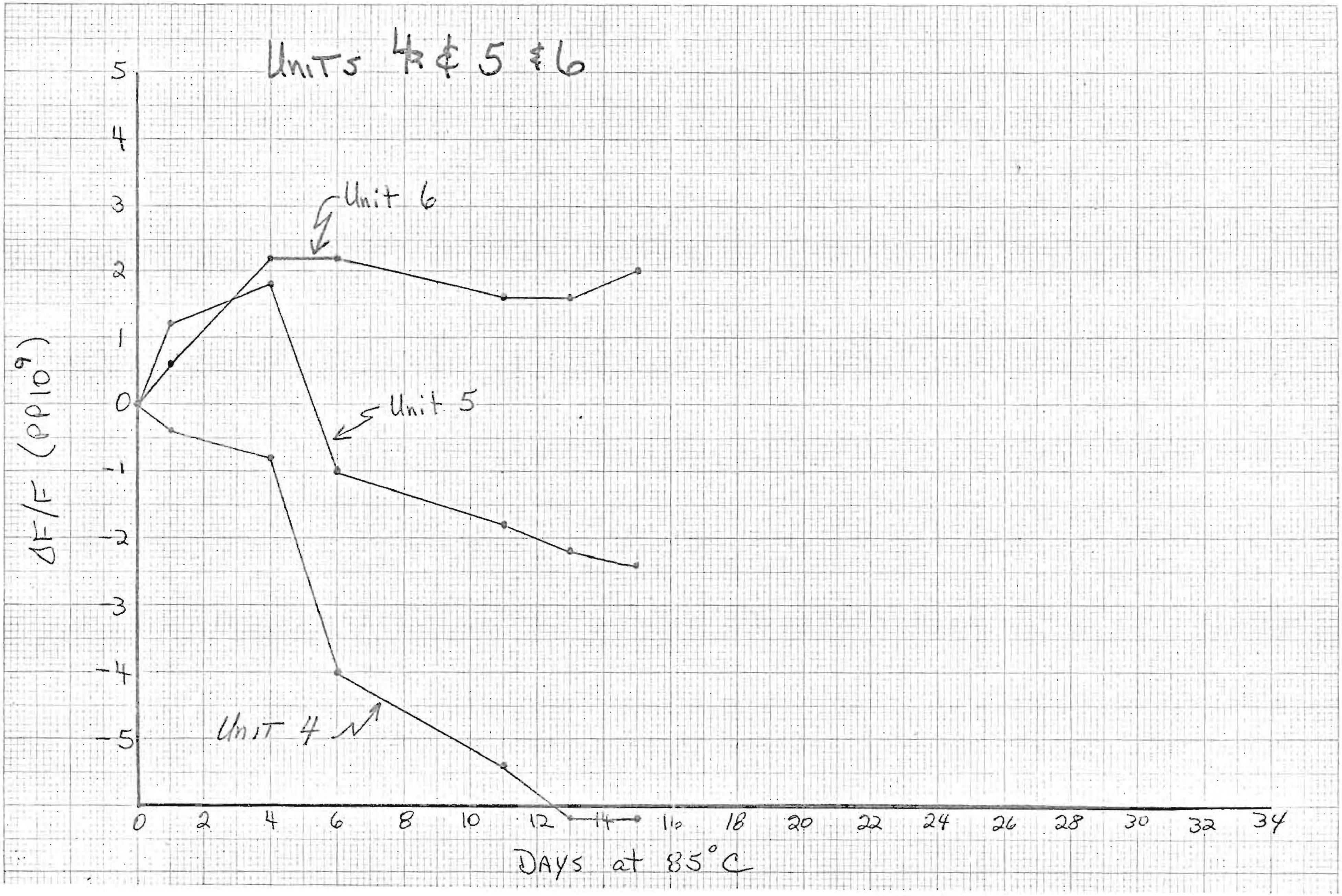


FIGURE 6 : AGING OF CRYSTAL RESONATORS NOS. 4, 5, AND 6

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May 30, 1972

Commanding General, A15 AAP
U. S. Army Electronics Command
ATTENTION: Solid State and Frequency Control
Division, AMSEL-KL-S
Fort Monmouth, New Jersey 07703

Contract Number: DAAB07-71-C-0301

Georgia Tech Number: A-1344

Subject: Monthly Status Report No. 8 Covering the Period 1 May to 31 May 1972.

Dear Sir:

During this report period we have accomplished the following:

1. Completed and processed the Semiannual Report.

2. Received delivery of the operational amplifier chips.

3. Modified construction of the hybrid oscillator.

4. Performed additional testing on the commercial crystal units.

5. Modified the mounting process for attaching the crystal holder to the base assembly.

6. Devised and evaluated a procedure for final temperature and frequency adjustment of the TMXO.

The semiannual report, which is due at the end of May, has consumed much of the available time during this report period. It was essentially finished at the time of writing this report and should be received by the contractor within a few days.

The operational amplifier chips for the temperature control circuit have finally been received, four months after the date of order. Work on the construction of this hybrid circuit has been resumed and no problems have been encountered to date in the assembly process. The extreme delay in obtaining the operational amplifier chips has, in our opinion, resulted in a minimum setback of 30 days for completion of the first prototype oscillator.

In Letter Report No. 7 the problems of bonding the aluminum leads supplied with the two MOSFET's we are using in the oscillator circuit to the gold conductor path on the alumina substrate was discussed. Further problems have developed in this area during the past month. Attempts to secure a good electrical contact between MOSFET leads and the gold film by using conductive epoxy at first appeared successful. After heating the oscillator though, performance would become erractic and eventually cease. Resistance checks were made between the MOSFET leads and the gold film in order to evaluate the epoxy bonds. During this testing it was discovered that many of the bonds exhibited a high resistance which could be lowered to a near short circuit by switching the volt-ohm-meter (VOM) to its highest range. The voltage at the test probe tips on this range was about 7.5V. Once the resistance dropped, the VOM was switched to the lowest range (probe voltage = 1.5V) and the bond between the epoxy and aluminum wire again became erractic and returned to a high resistance. The DC operating voltages on the MOSFET drain and source are approximately 7.0V and 1.0V respectfully and the erractic performance of the oscillator was due to these wire bonds.

The cause for this behavior of the bonds is believed to be oxide formation on the aluminum leads. These leads are subjected to temperatures up to 300° C during removal of the chip from the TO-72 package and for longer periods at 150° C during the epoxy curing steps. This oxide apparently breaks down at voltages of about 7 volts and then rapidly reforms a new continuous film.

When we started to evaluate our oscillator design last February, we were informed by the local RCA representative that RCA type 40673 MOSFETS were not obtainable in unencapsulated form. After the bonding problem discussed above was isolated, a phone call to the RCA Applications Group in Summerhill, N. J. was made and it was learned that the RCA 40673 is indeed available in chip form. They arranged to ship us 25 transistors on a sample basis, with a two week delivery time. The chips have to be mounted to the board by die-bonding and the flying gold leads bonded to the gold film on the chip by thermal compression (TC) bonding. This has been done satisfactorily on rejected practice MOSFET chips.

Because of the two week delivery time an alternate solution to the problem is being attempted on the present oscillator. As stated in Letter Report No. 7, good bonds have been made between aluminum MOSFET leads and vacuum deposited gold films on polished quartz and glass surfaces. A polished fused quartz wafer was plated with gold and diced to various size chips compatible with microcircuit devices. These chips were epoxied to the oscillator substrate next to the MOSFET chips. The aluminum MOSFET leads are then TC bonded to the gold film on the fused quartz chip and a gold flying lead used to complete the connection between the quartz chip and the gold film on the substrate. Figure 1 illustrates this procedure. This technique appears to be satisfactory in lieu of waiting two weeks for MOSFET chips without attached leads to arrive.

Other modifications to the oscillator were made to compensate for stray capacitance and MOSFET gain. Capacitors C_b and C_c in Fig. 2 are now 62 and 56 pF respectively. Ca is 150 pF and C_d will be set between 1 and 33 pF. Resistor R_1 was changed to 10k in order to increase the output of the oscillator stage and R_6 was changed to 8.2k to increase the gain of the buffer stage. The latter two changes were necessary because the gain of the two transistors presently in the circuit are lower than previous units.

The UTP temperatures on the five crystal units were determined and found to be slightly higher than desired. The specification given to the manufacturers was $85^oC \pm 3^oC$. All units have an UTP of around $89-90^oC$. Figure 3 is the frequency/temperature variation of Unit 6 which is typical of all five units.

Fast warm-up tests on Unit 6 have indicated warm-up characteristics similar to crystals produced in-house which were used in previously conducted thermal system experiments.

A thin film heater has been bonded to Unit 6 and this in turn attached to the pedestal of the base assembly. Because the crystal is mounted in a HC-6 slim-line holder, the crystal holder cannot be spot-welded to the pedestal because of the narrow flange. Instead the following method was used. An alumina wafer 3/16 x 1/8 x .025 inches was attached to the top of the pedestal with a vacuum compatible epoxy adhesive TORR-SEAL.(1) This adhesive has very good shear strength as well as extremely low-outgassing up to 250^oC. The crystal holder was then attached to the pedestal by an epoxy bond of Torr-Seal between the crystal flange and the alumina wafer. This method is believed to be stronger than attaching the crystal by spot welding to the pedestal due to the larger mating surfaces and the strength of the adhesive being used. An alumina wafer was used for two reasons. Firstly, to provide a thermal filter between the heated crystal holder and the stainless-steel pedestal. Calculations have shown that heat loss from the isothermal region through the pedestal would have been unacceptable with the TMXO operating in the lowest ambient temperature conditions. Secondly, it provides the option of operating the crystal holder ungrounded. This latter action will be necessary if Q2 of the temperature circuit must be removed from the BeO substrate and attached directly to the can with conductive epoxy adhesive to enhance the heat transfer between the two items. Normally the HC-6 holder will be grounded by a short length of 10 mil nickel wire between the holder and stainless steel pedestal.

A procedure for final temperature and frequency adjustment has been worked out. Before the frequency adjusting components in the oscillator can be selected the crystal must be at the operating temperature. The operating temperature is logically chosen to be at the UTP of the crystal to minimize frequency variations due to small temperature flucuations, after the initial warm up period. To set the temperature sensing bridge of the control circuit the following method will be used. Firstly, the crystal heater will be connected to an external DC supply so the crystal temperature can be increased slowly. The frequency of the crystal will be continuously measured by a synthesizer driven bridge with the crystal in one arm of the bridge. The crystal will not be connected to the hybrid MOSFET oscillator at this time. The temperature will be increased until the UTP temperature is reached as indicated by the frequency.

---

(1)Obtainable from Varian Associates

Since the frequency will be continuously monitored to the second decimel, the UTP can easily be recognized. The heater will then be connected to the control circuit (see Fig. 4) and the temperature set arm of the sensing bridge, R_{4a} and R_{4b} can then be adjusted until the UTP frequency is duplicated as closely as possible. Resistor R_{4b} is adjustable in 25 ohm steps by bonding to different pads. After the temperature has been set and the crystal connected to the MOSFET oscillator, the frequency is adjusted with C_d, Ra, Rb, Rd, and Rv (see Fig. 2) to $\pm 1 \times 10^{-10}$ of 5 MHz while the crystal is at the operating temperature.

Progress anticipated during the next report period should consist of:

1. Completion of temperature control hybrid circuit.

2. Final assembly of first prototype with possible exclusion of insulation placement and sealing.

3. Extensive testing of completed TMXO prior to sealing.

4. If no serious problems occur, final sealing will be done and final testing started.

Respectfully submitted,

Raymond K. Hart
Project Director

RKH/mdh

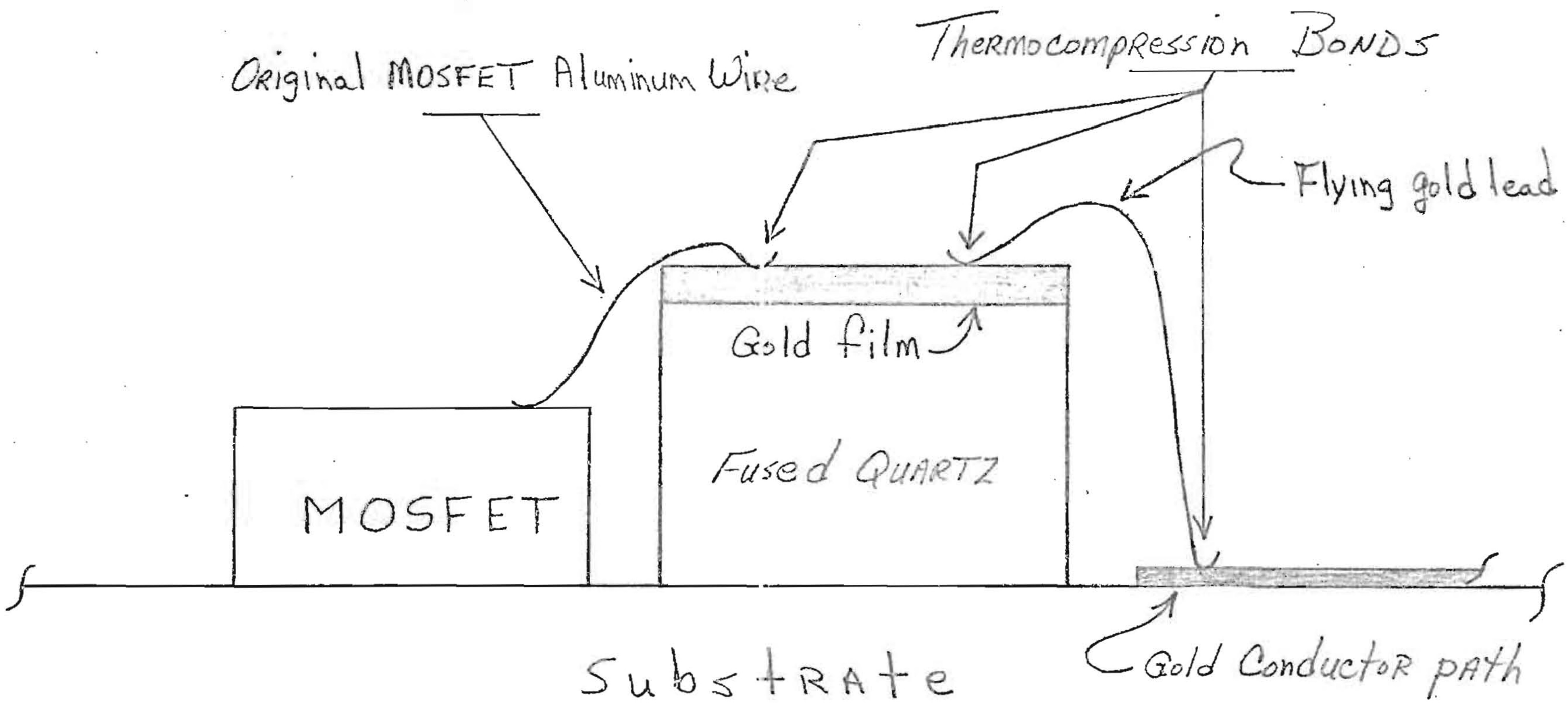
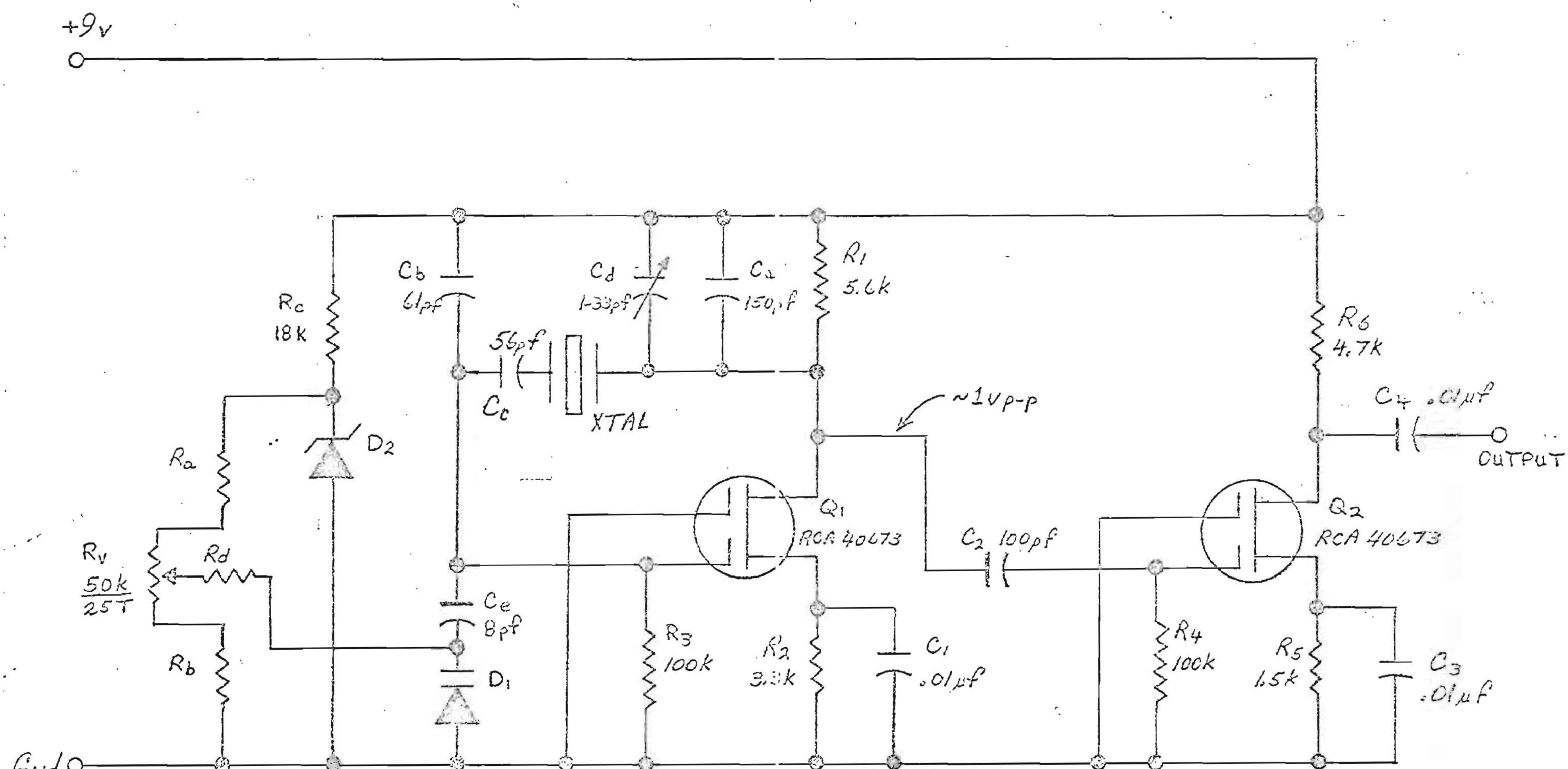


FIGURE 1: Present lead bonding technique for MOSFET Q_1 and Q_2. All leads bonded in this manner.

FIGURE 2: MOSFET CRYSTAL OSCILLATOR



Ra, Rb, and Rd selected for final frequency adjustment

5-4-72 8al

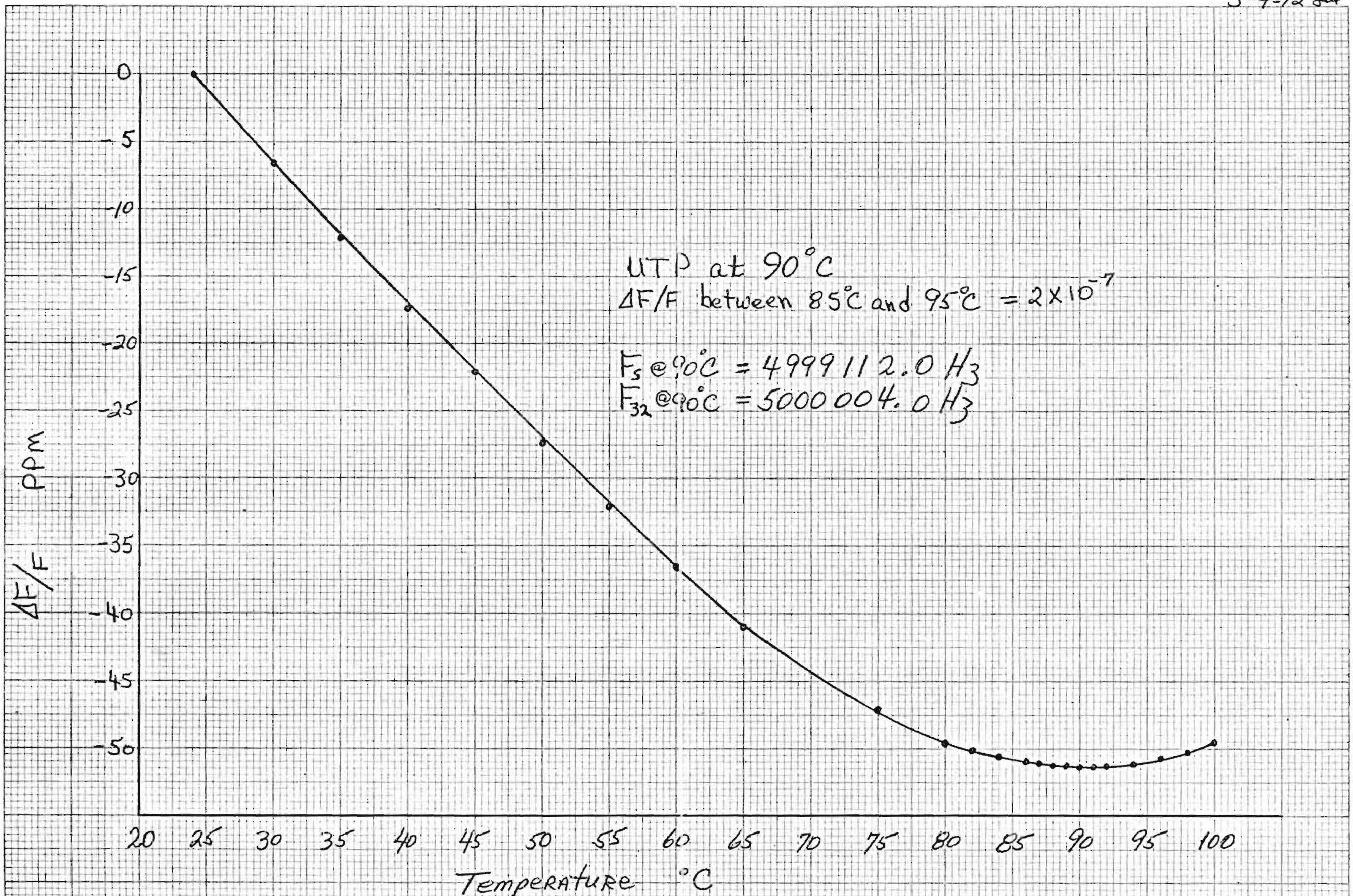
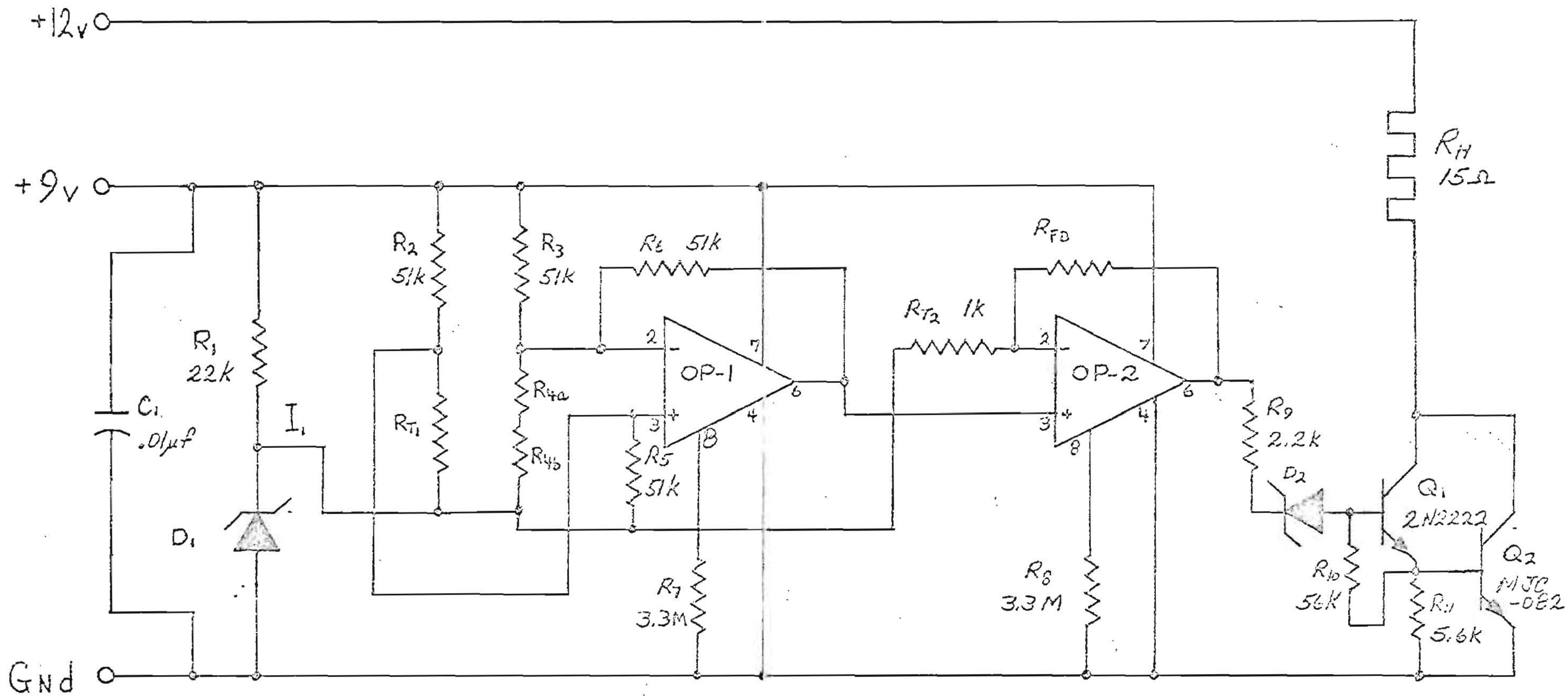


FIGURE 3: TEMPERATURE COEFFICIENT of FREQUENCY of UNIT #6



OP-1, OP-2 : μA776
D_1, D_2 : MZC4.7B1 MOTOROLA
R_{T_1} : VECO THIRISTOR TYPE FN1A6
R_4 : TRIM TO SET TEMPERATURE

FIGURE 4: TEMPERATURE CONTROL CIRCUIT

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July 6, 1972

Commanding General, A15 AAP
U. S. Army Electronics Command
ATTENTION: Solid State and Frequency Control
Division, AMSEL-KL-S
Fort Monmouth, New Jersey 07703

Contract Number: DAAB07-71-C-0301

Georgia Tech Number: A-1344

Subject: Monthly Status Report No. 9 Covering the Period 1 June to 30 June 1972

Dear Sir:

During this report period we have accomplished the following:

1. Completed fabrication of hybrid temperature control circuit and experienced problems concerning the fabrication and reliable operation of this circuit.

2. Completed additional investigations into the performance of the oscillator circuit.

The first hybrid temperature control circuit was completed and has been undergoing testing and repairing over much of this report period. The first problem encountered with this circuit was associated with zener diode D_1 (see Monthly Status Report No. 8, Figure 4). It was discovered during the check-out of the completed circuit that this diode was not performing properly. Further tests revealed that these diodes had evidently been mislabeled by the supplier and we were actually supplied with high level zeners. The circuit design calls for a low level zener which can maintain its rated voltage at zener currents down to 250 μA. Telephone calls were placed to various contacts at Motorola and also to another manufacturer in an attempt to get the proper diodes without going through the delay of normal purchasing channels. In about one week the proper diodes were received and placed in the circuit. Resistor R_1 was changed to 7.5KΩ to increase the zener current due to larger than expected load current (I_1) variations.

At this point the circuit appeared to be performing as expected and was mounted to the side of the HC-6 holder for temperature calibration of the bridge network. Control transistor Q_2 and thermistor R_{T_1} were mounted to the top of the can in the manner previously described in Section II-C-4 of the Semiannual Report. Experimental determination of resistance values for R_{4_a} and R_{4_b} was accomplished as outlined in Monthly Status Report No. 8. When selecting these components it was necessary that their TCR be taken into consideration. Since the circuit was now mounted to the side of the crystal can, a special holding vise with teflon jaws was constructed to secure the assembly for wire-bonding operations on resistor R_{4_a}. The wire-bonder uses a hydrogen flame torch for ball forming and wire cutoff operations. This flame evidently came into contact with the teflon jaws a few times during the wire-bonding. The by-products of this combustion include hydrofluoric acid and fluorine, which evidently began to attack the aluminum surfaces of all the active devices on the substrate. Operational problems started occurring almost immediately with this circuit and within several days after the initial use of the teflon-jawed holder it was noticed that the aluminum surfaces of the diodes, op-amps, and transistors were either extremely corroded or missing entirely. Wire bonds to the pads of these devices were naturally affected and the circuit ceased to operate at all. Difficulty in repairing microcircuits is well known but we succeeded in replacing all the affected components. After the cause of this problem was found the jaws of the holding vise were changed from teflon to aluminum. We have not observed any additional problems of this nature. However, there are still other problems to remedy, the major one being the unreliability of the wire-bonding to the operational amplifiers. The aluminum bonding pads on these devices are about 2 sq. mils. Stitch-bonding 0.0007" diameter gold wire to these pads has resulted in an approximately 25% bond failure. It has also been responsible for having to again replace both operational amplifiers, a time consuming process in addition to being very difficult. The most reliable technique for the TC bonding of gold wire to aluminum films is ball-bonding but generally requires pad areas larger than 2 sq. mils. Attempts are now being made to attach the wires to the operational amplifiers by the combined use of ball-bonding and subsonic vibration. Initial bonds using this technique have been superior to previous bonds but are difficult to make without shorting adjacent conductors on the amplifiers. Both amplifiers will be replaced and the ball-bonding with vibration will be used to attach the gold leads to the bonding pads. If the bonds prove secure both electrically and mechanically then Delta Bond 152 epoxy will be applied to the tops of the amplifiers, as was done with the MOSFET chips, to provide some degree of protection for the bonds from further handling. Regrettably, these problems have delayed progress and no reliable data regarding warm-up time, short-term temperature stability and other performance parameters of this prototype device can be passed on at this time. Observations during the bridge calibration indicate that mounting Q_2 on the crystal can does degrade the warm-up time slightly and possibly affects the short-term temperature stability as well.

Additional performance checks have been carried out on the hybrid oscillator circuit. The circuit was placed into an 85°C high stability oven with the exception of frequency adjustment potentiometer, Rv, and resistors Ra, Rb, and Rd which were located outside the oven. These resistors have values of 120 KΩ, 180 KΩ, and 1MΩ respectively. The tuning range under these conditions is 4 X 10^{-8} from end to end of Rv. Although this is a higher tuning range than the Technical Guidelines specify, the frequency should still be adjustable to 5 MHz with a resolution of ±1 X 10^{-10}. The added range could compensate for other factors such as crystal aging, hysteresis, and initial frequency setting.

While the oscillator circuit was in the 85°C oven the temperature sensitivity of the tuning control, Rv, was checked by increasing its temperature from 25°C to approximately 100°C. The output frequency was monitored with a resolution of ±1 X 10^{-9} but no change in the frequency was observed. It is believed that the -40 to +75°C ambient temperature variation that Rv must be exposed to will not affect the frequency stability of the oscillator.

Past experiments to determine the frequency/voltage sensitivity of the hybrid oscillator were performed without the tuning network included in the circuit. A sensitivity of about 1.2 X 10^{-11}/mV change in supply voltage can be attributed to the oscillator and buffer stages. With the tuning network included the frequency/voltage sensitivity has been determined to be about 4 X 10^{-11}/mV change in the +9V supply. The values for the tuning network components for this experiment were as follows:

Ra = 120 KΩ

Rb = 180 KΩ

Rc = 18 KΩ

Rd = 1 MΩ

Rv = 50 KΩ/10 turn

Ce = 8.2 pF

Diodes D_1 and D_2 remain as previously reported.

With the circuit still in the 85°C oven, an opportunity was provided to evaluate the effect on frequency of applying power to the circuit while being independent of temperature. One benefit of such an experiment is a check of the effect of crystal power dissipation on the frequency. Power was removed for periods ranging from 5 seconds to 5 minutes. When power was reapplied to the circuit, frequency offsets of about +1 X 10^{-8} maximum were observed. Restabilization to the initial frequency took from 1-3 seconds after the shorter power interruption periods to about 20-30 seconds after the longer power interruption periods. These times and frequency offsets indicate that the output frequency during the initial 1 minute warm-up period will not be affected by self-heating of any oscillator component, including the crystal. The calculated and measured power dissipation of the crystal during this test was 6 μW.

One additional experiment concerning oscillator performance was accomplished during the past month. This was to determine the temperature coefficient of frequency due to oscillator components other than the crystal. The crystal and oscillator were separated physically and the temperature of the oscillator varied between 25°C and about 90°C while the crystal was maintained at 25°C. The total frequency change observed over this temperature differential was 1.8 Hz. Thus the TCF contributed by the oscillator components is about $5.7 \times 10^{-11}/0.01°C$.

Progress anticipated during the next report period should consist of:

1. Final assembly of first prototype.
2. Extensive testing of completed TMXO prior to sealing.
3. If no further serious problems occur, sealing will be done and final testing completed.

Respectfully submitted,

Raymond K. Hart
Project Director

RKH/jl

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

ECOM-0301-1

TACTICAL MINIATURE CRYSTAL OSCILLATOR

Semiannual Report

By

R. K. Hart and W. H. Hicklin

AUGUST 1972

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TECHNICAL REPORT ECOM-0301-1
August 1972

Reports Control Symbol
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TACTICAL MINIATURE CRYSTAL OSCILLATOR

Semiannual Report

1 July 1971 to 31 May 1972

Contract No. DAAB07-71-C-0301
DA Project No. C8-1-04302-01-C8-CA
Task No. 02

Prepared by

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For

U. S. Army Electronics Command
Fort Monmouth, New Jersey

ABSTRACT

The purpose of this work is to design and construct exploratory development models of a fast warmup 5 MHz tactical miniature crystal oscillator (TMXO). The total package is to be contained within a volume not to exceed 5 cubic inches, operate in an ambient temperature range of -40 to 75 °C with a maximum permissible frequency deviation of $\pm 1 \times 10^{-8}$. Available power to heat the temperature sensitive elements of the TMXO from ambient to 85 °C in one minute is 10 watts; operating power after warmup will be limited to 250 milliwatts. An output frequency deviation, after a 30 day stabilization period, of less than $\pm 2 \times 10^{-10}$ per week is required, as well as a short term stability of $\pm 1 \times 10^{-11}$ for periods of time ranging from 1 sec to 20 min. To conserve space and power, both the oscillator and temperature control circuits are of the hybrid microcircuit variety. An encapsulated frequency adjustment potentiometer is provided with the adjustment control accessible from outside the hermetically sealed oscillator.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

I. INTRODUCTION

The general design concept described in the interim report[1] submitted after the study phase of this project has generally been followed.

There were, however, certain changes that were considered necessary. For example, the oscillator has been completely redesigned. The present oscillator uses dual gate, depletion type, metal oxide semiconductor field-effect transistors (MOSFET) of the RCA type No. 40673. Such a device is the solid-state equivalent of a vacuum tube, requires no driving power, and, as will be shown, has a built-in signal-leveling effect.

The temperature sensitive gain feature of the temperature control circuit was eliminated, since experiments showed that a carefully selected, fixed-gain condition was preferred.

The use of shrink bands to lock the resonator, heater, and hybrid circuits together was found to be unreliable. As an alternative, thermally conducting epoxy (Delta Bond 152) is being used to secure these components.

Access to the frequency trimming potentiometer (Bourns No. 3280L) is essentially the same, but the location was changed to the base of the holder as will be described later. The voltage regulator (Fairchild No. MA723) is similarly located. Neither of the latter two components will be located in the isothermal region of the TMXO, and thus will not be under temperature control.

A modest amount of redesign resulted when the vibration requirement was added to the mechanical specifications. The stainless-steel core support pedestal was one of the concessions made. However, if the thermal conductance of the stainless steel support proves to be too high, we are prepared to replace it with a VESPEL (polyimide) support. This modification would also require an additional electrical conductor since the stainless steel support is also being used as the ground return for the system.

II. EXPERIMENTAL APPROACH

A. Preamble

All of the various parts which comprise the TMXO have been constructed in the final form except the temperature control circuit. The latter circuit requires two operational amplifiers which have yet to be received. A modest modification was required to successfully attach the MOSFETs* to the hybrid oscillator circuit chip.

We have not yet assembled, evacuated, baked, and sealed the complete package. Anticipated trouble spots are described in the following paragraphs.

1. Frequency Adjustment

The load capacity facing the crystal unit and the varicap biasing network are installation adjustments that must be done at the upper turning point (UTP) temperature before the package is closed. The goal is to set the frequency to the midpoint tuning range of the trim pot since the direction of frequency drift under the specified operating conditions cannot be anticipated.

2. Temperature Adjustment

To meet both the warm-up requirements and the frequency/temperature stability requirements the crystal must be operated as close to the UTP as possible. The crystal units we will use have UTP's of ~ 88 to 89 °C. Our tolerance specification on the UTP to the manufacturer was 85 °C ± 3 °C. Given a choice, we would have preferred crystals with the UTP at 82 °C, since high UTP's adversely affect both warm-up time and input power.

3. Evacuation of NRC-2 Insulated Package

We must carefully enclose the isothermal core of the package with NRC-2 super insulation to obtain the desired insulation. The literature describing the use of NRC-2 states that "cocooning" must be avoided. We can, however, perforate the insulation in suitable places so as to allow the escape of gas from the isothermal region as well as from the space between the layers of insulation. We will need enough holes in the material to provide sufficient gas flow, but the layers must be opaque to radiation from the core to the outer wall. NRC-2 can be purchased already perforated, but we preferred to make our own hole pattern.

4. Vacuum Bakeout

The bakeout after evacuation may be more difficult than it appears at first glance. If the insulation performs as expected, heating the exterior will not heat the interior of the enclosure, nor will heating the core provide the heat needed to properly outgas the layers of insulation. At the present, the solution to the problem of uniform heating of the interior of the containment vessel seems to be the following:

---

*Initially these were removed from the TO-72 holder and rebonded to our circuit, but we now find that they were available from the manufacturer in chip form.

(1) exhaust the vessel to the lowest obtainable pressure,

(2) back fill with a noble gas (probably argon) to about one torr, and heat the core and outer wall of the type D enclosure. The high gas pressure will permit heat transfer by convection and uniformly heat the core, insulation and other parts of the enclosure that require outgassing. The system must then be very rapidly pumped to a low pressure while still hot. This process may require an accessory liquid nitrogen trapped oil diffusion pump in order to adequately pump the noble gas from the system. We also intend to vacuum outgas the NRC-2 insulation at $\sim 100\ ^\circ C$ before we use it.

5. Shock and Vibration

A number of vibration tests have been made on individual parts of the system. More are anticipated of course. We do intend to thoroughly check the mechanical properties of the total package after final assembly, but before final sealing.

6. Frequency Aging and Recovery

We consider the specified aging of $\pm 2 \times 10^{-10}$ per week to be generally beyond the state-of-the-art for manufactured units of the type we must use. Our initial plan was to fabricate a number of units early in the program, place them on aging test at 85 °C and select the best for use in the TMXO. The same general method of pre-selection would have applied to the retrace requirement ($\pm 3 \times 10^{-9}$ for five restarts from -40 °C, ambient). With purchased resonators, we consider the aging and retrace problem to be generally beyond our control.

B. Apparatus

All the major equipment required for the various phases of this project is on hand at the Engineering Experiment Station. The facilities of the quartz resonator research group are available and include a secondary frequency standard, constant temperature ovens, frequency synthesizer, recorders, computing counter, vector volt meter, etc. Some of the above items are housed in an electrically shielded screen room. In addition to the electronic equipment, four vacuum systems are available; two are liquid nitrogen trapped oil diffusion pumped systems for rough work and two are ultrahigh vacuum, ion-pumped systems. The vacuum equipment is housed in a clean room area which also includes a wet-cleaning facility, a photo resist processing room, and a bonding room containing ultrasonic and thermo compression bonding equipment.

The microcircuit assembly facility includes a probing station (Dumas Model D-300), ovens for curing epoxy and of course microscopes. A precision diamond saw is also available for dicing ceramic substrate materials.

The mechanical test facility includes a Vibramatic test system* having two each No. 2120MB amplifiers and an EA 1500 exciter. The amplifiers are driven by an HP Model 202C audio oscillator. A strob light (Strobotac Type No. 631B) and an oscilloscope (Tektronix Type 532-S7) completes the installation.

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*MB Electronics.

C. 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 present package, as described in Report TR ECOM-0301 (Interim) consists 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. The layout for the parts mounted on the header is shown by Fig. 2. 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.

The volume of the containment vessel is less than 5 in^3 and thus meets the maximum volume specification.

2. Resonator Selection

On September 10, 1971 the Contracting Officer's Representative recommended that we purchase, rather than assemble in-house, the quartz crystal units for this project. Crystal units were ordered with the following specifications.

(1) Frequency: 5,000,000 Hz ± 25 Hz @ 85 °C.

(2) Upper turning temperature: 85 °C ± 3 °C.

(3) Load capacity: 32 pF.

(4) Mechanical requirements:
  a. Shock: 30 g max.
  b. Vibration: 0.06" peak to peak @ 5 to 55 Hz.

(5) Holder: HC-6, cold weld.

(6) Special features: holder to be evacuated, baked, and backfilled with 50 torr of helium.

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*All State Welding Alloy Co., White Plains, N. Y.

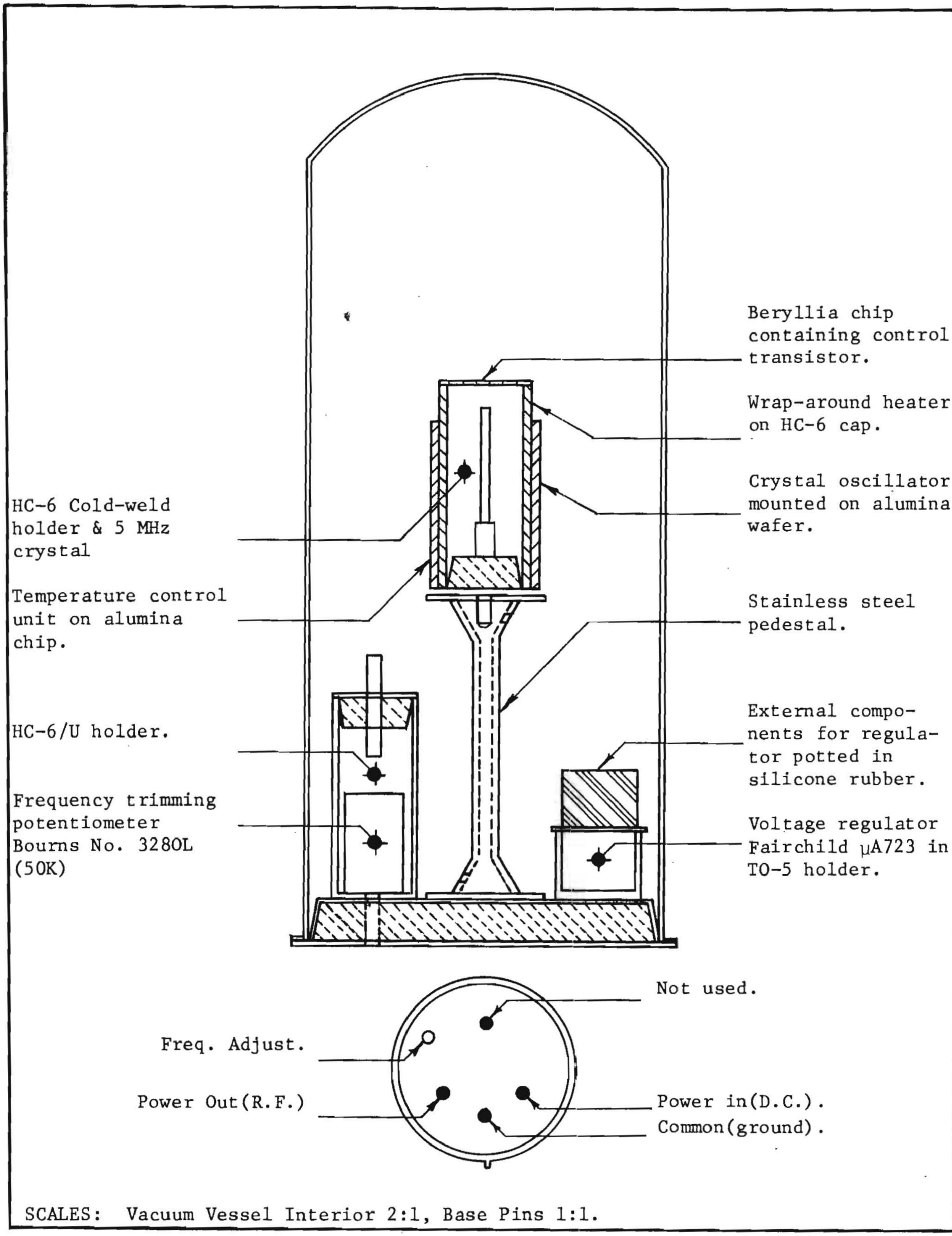

Fig. 1. Conceptual design of tactical miniature crystal oscillator mounted in a type "D" cold-weld holder.

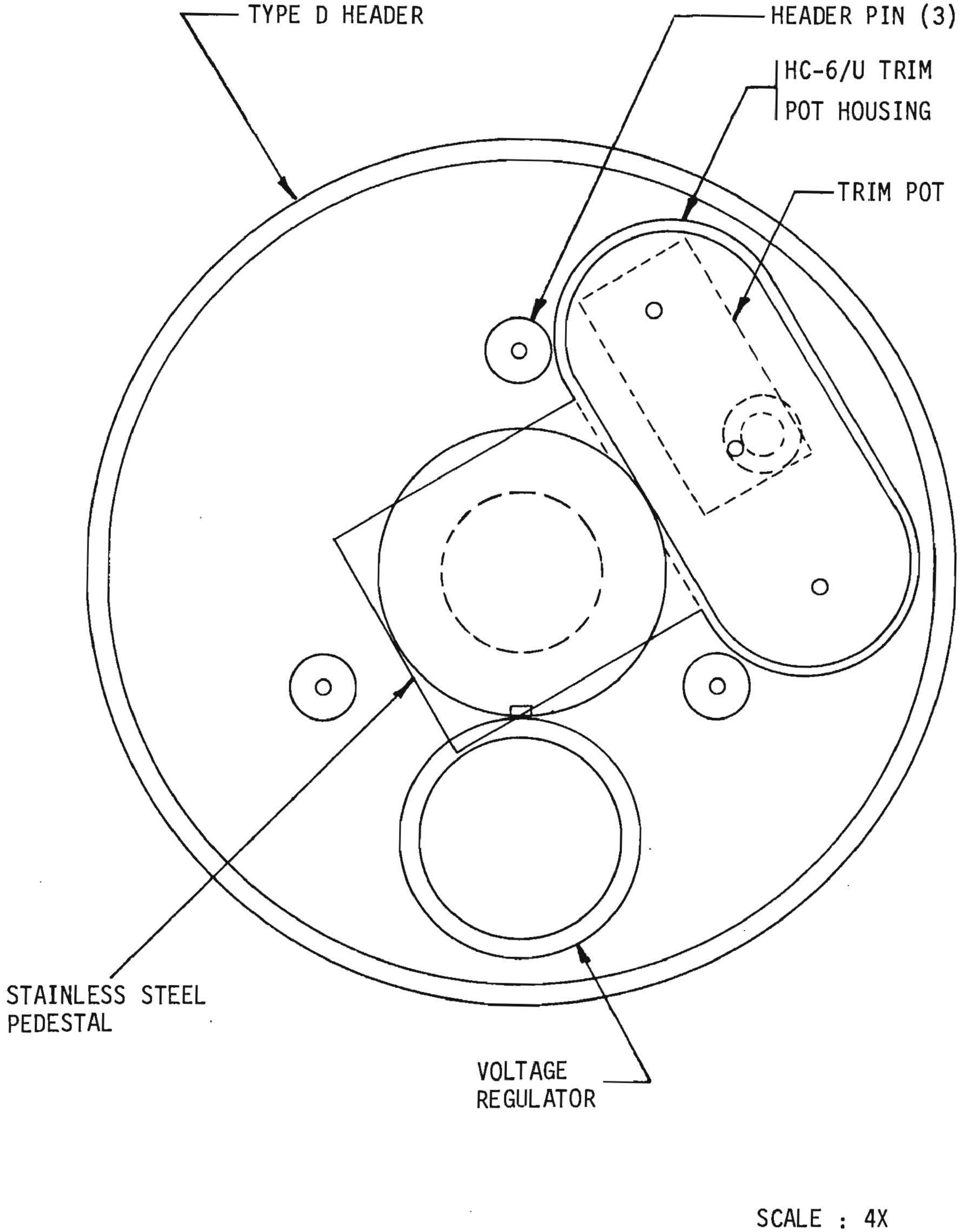

Fig. 2. Layout of components on the type "D" base. Crystal holder on the pedestal is positioned so the pins are on line A-A.

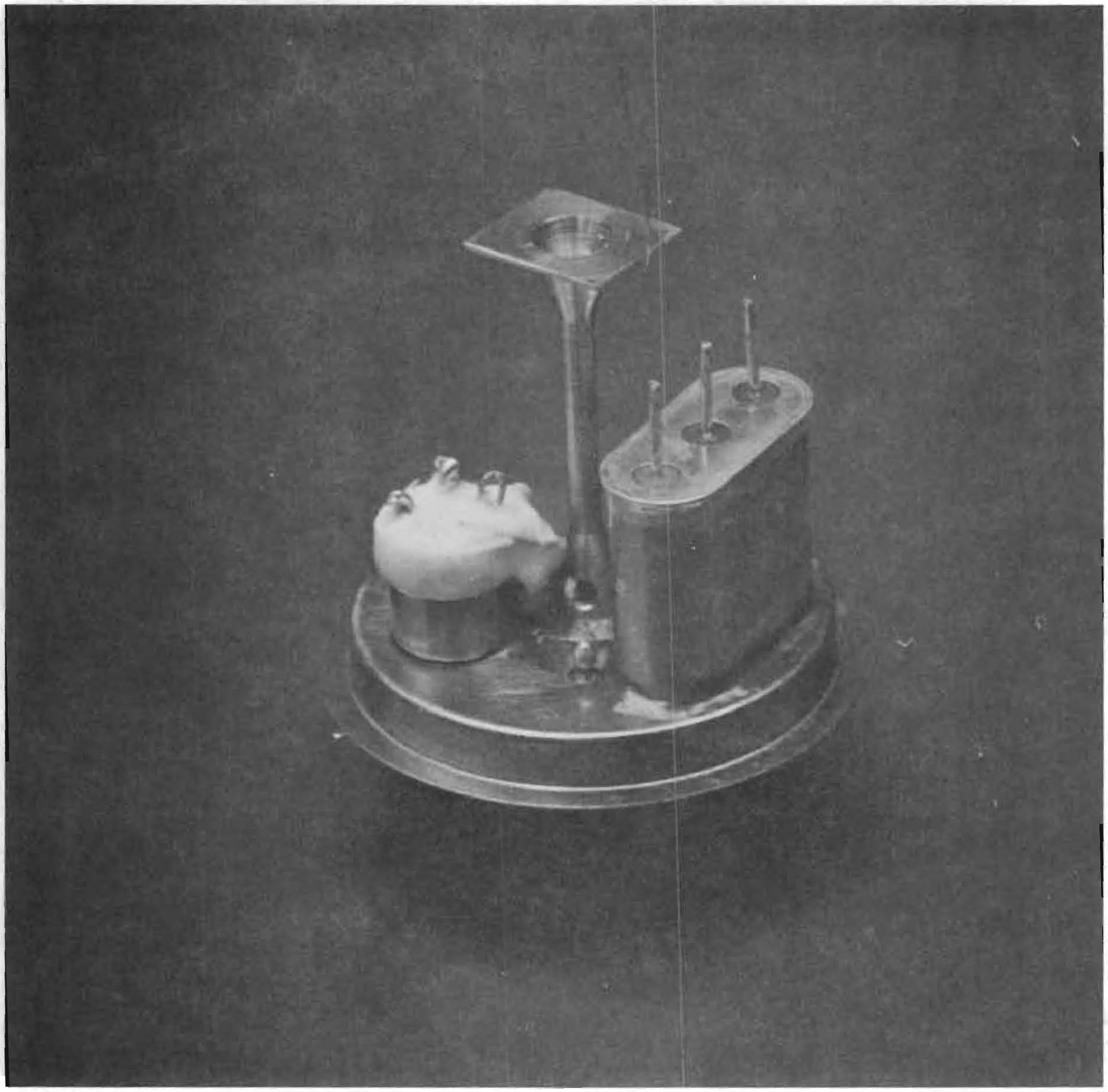

Figure 3. Photograph of Base Assembly

Figure 4. Photograph of Extended Type "D" Cap

The use of helium-filled resonator holders for fast thermal response was described by Hicklin and Bennett[2]. It was further specified that the units be fabricated from fundamental plates due to the fast warm-up requirements. We felt that to specify an aging requirement of $\pm 2 \times 10^{-10}$/ week on the units would place an insurmountable burden on the supplier since such aging is generally beyond the state-of-the-art.

3. Resonator Support

The design of the isothermal-core support is shown in Fig. 5. The lower (round) flange is spot-welded to the type D base. The upper rectangular flange was designed so the untrimmed sealing flange of the HC-6 holder could be spot-welded to it. However, the crystal units were delivered in slim-line type holders without a flange. The actual method of attaching the crystal unit is the following. First, attach a piece of alumina 7/16" X 3/8" X 0.025" to the upper pedestal flange with low-vapor-pressure resin.* Then the resonator assembly is attached with Torr Seal to the alumina. The function of the alumina is to inhibit the loss of heat from the crystal unit and to allow the option of operating the crystal can grounded or ungrounded. In the latter case, the heater control transistor could be attached directly to the can for maximum heat transfer.

4. Location and Support of Electronic Circuits

The voltage regulator and frequency-trimming potentiometer (trimpot) are located on the base as described in Section II-C-1. Access to the screw adjustment of the trimpot is a hole through the base. The trimpot is mounted in a sealed HC-6/U holder which is sealed to the base over the access hole in such a way that the interior remains at atmospheric pressure.

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 1/2" X 5/8" X 0.015". These circuits and their method of fabrication will be described in a subsequent section. The alumina is then 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, will be located on top of the HC-6 holder. These devices cannot be attached directly to a grounded holder. The transistor will be mounted on a thin, beryllia chip which will be epoxy bonded to the holder. The thermistor chip will be epoxied directly to the holder. Short flying leads will connect each device into the circuit.

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*Torr Seal^R from Varian Associates.

**Thermofoil Heater, Minco Products, Inc.

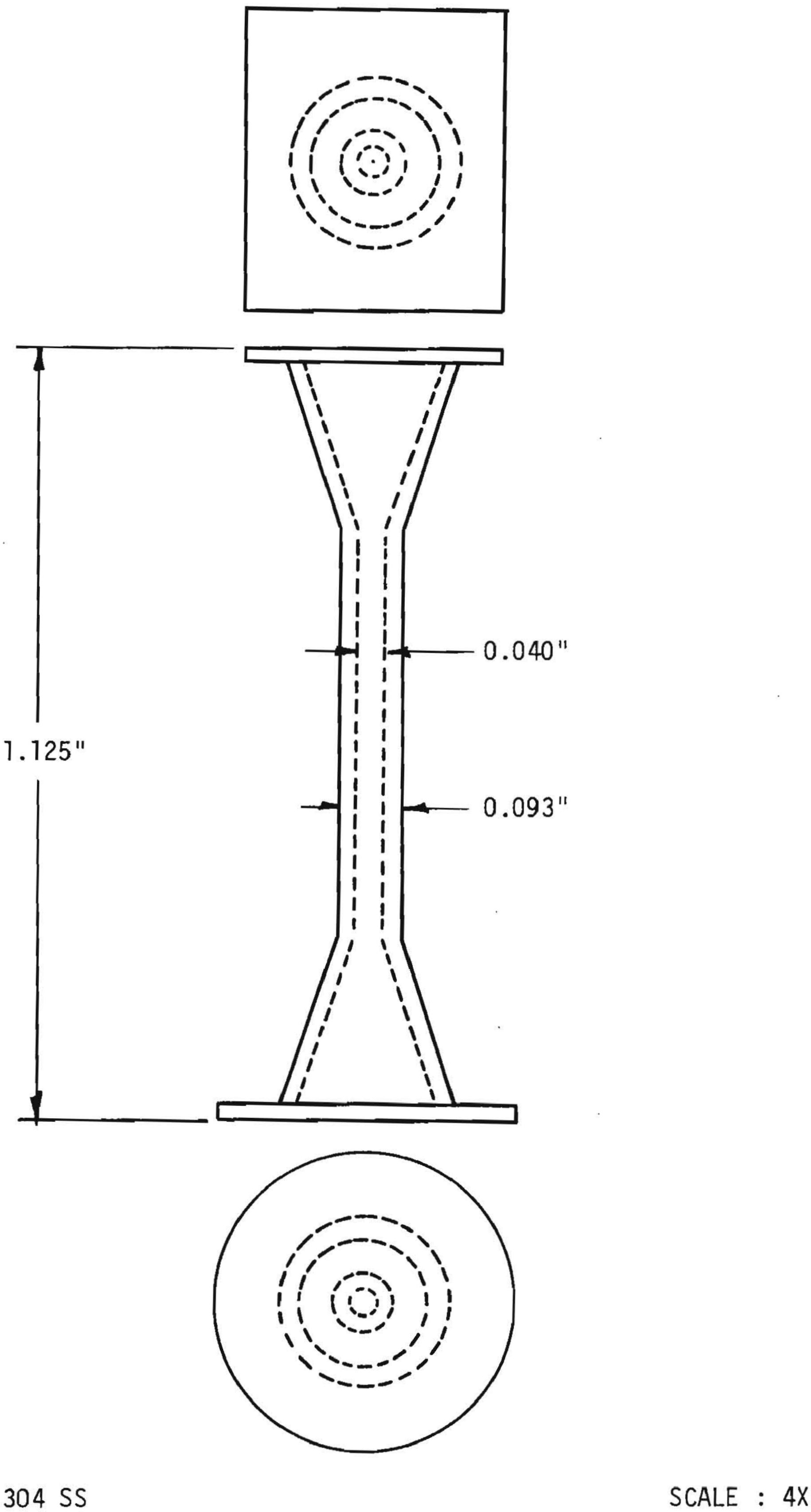


Fig. 5. Stainless steel support pedestal. Lower (round) end spot-welds to type "D" base. Upper (rectangular) end attaches to HC-6 holder.

5. Electrical Leads

In selecting the electrical lead material and 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 a high resistance--about 65 times greater than copper. Nickel possesses a reasonable balance of good electrical resistance (five times copper) and low thermal conductivity (about 1/6 of copper). The leads will therefore be 10 mil nickel. The resistance of such wire at 25 °C is ~ 0.7 Ω/ft. The heater-power lead will be about two inches long (~ 0.1 Ω). During warmup the input current will be about one amp so the nickel lead will dissipate ~ 0.1 watt. After one minute the lead dissipation will be negligible. The ground return for both the dc input power and the RF output power is the stainless steel support pedestal.

6. Thermal Insulation

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 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 2×10^{-5} W cm/cm^2 ΔT. Few materials approach within even one order of this value. The plastic foam insulators have K values of 2×10^{-4} or more depending on their density. Two types of "super insulation" are available. 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 4.1×10^{-7} W cm/cm$^2\Delta T$, 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. We will use cold welding for the final seal and during evacuation the die will partially open to provide a high conductance path for gases liberated during bakeout.

The use of a getter inside the vacuum vessel to help maintain the pressure requirement is indicated and barium powder getters tablets 1/2" dia. X 1/8" (Linde) were obtained. These arrived in a badly damaged condition which according to the manufacturer is normal when roughly handled. Such a fragile getter was rejected for our particular application. Instead, we will use strips of Cer Alloy^{R} 400 (Ronson Metals) spot welded to the inside of the holder. The efficiency of this getter is low at room temperature, but it should provide reasonable gettering of desorbed gases at bakeout temperatures.

7. Discussion

The design goals for the thermal and mechanical considerations were to provide a compact, well-insulated and mechanically-stable package. The controlling design specifications are those which set the limit on size (< 5 in^3), maximum power consumption (250 mW after warmup), and shock and vibration (MIL-STD-202D). The success of our design has yet to be proven--due mainly to the extreme difficulty we have had obtaining prototype quantities of electronic components needed before final assembly is possible. Individual sections have of course been tested; the stainless-steel support pedestal with attached crystal holder and alumina circuit have been given vibration tests. No resonances were found over the range of 5 to 55 Hz. The additional weight of the electronic components will only increase the mass by a very small amount and will not be sufficient to lower the first resonance into the frequency range of interest.

The assembled device requires the use of many different materials, all of which must be vacuum compatible. We have not tested all of the materials that will be used in this TMXO. For those materials we have not tested, the specifications of responsible manufacturers were accepted as valid.

D. Electronic Circuitry

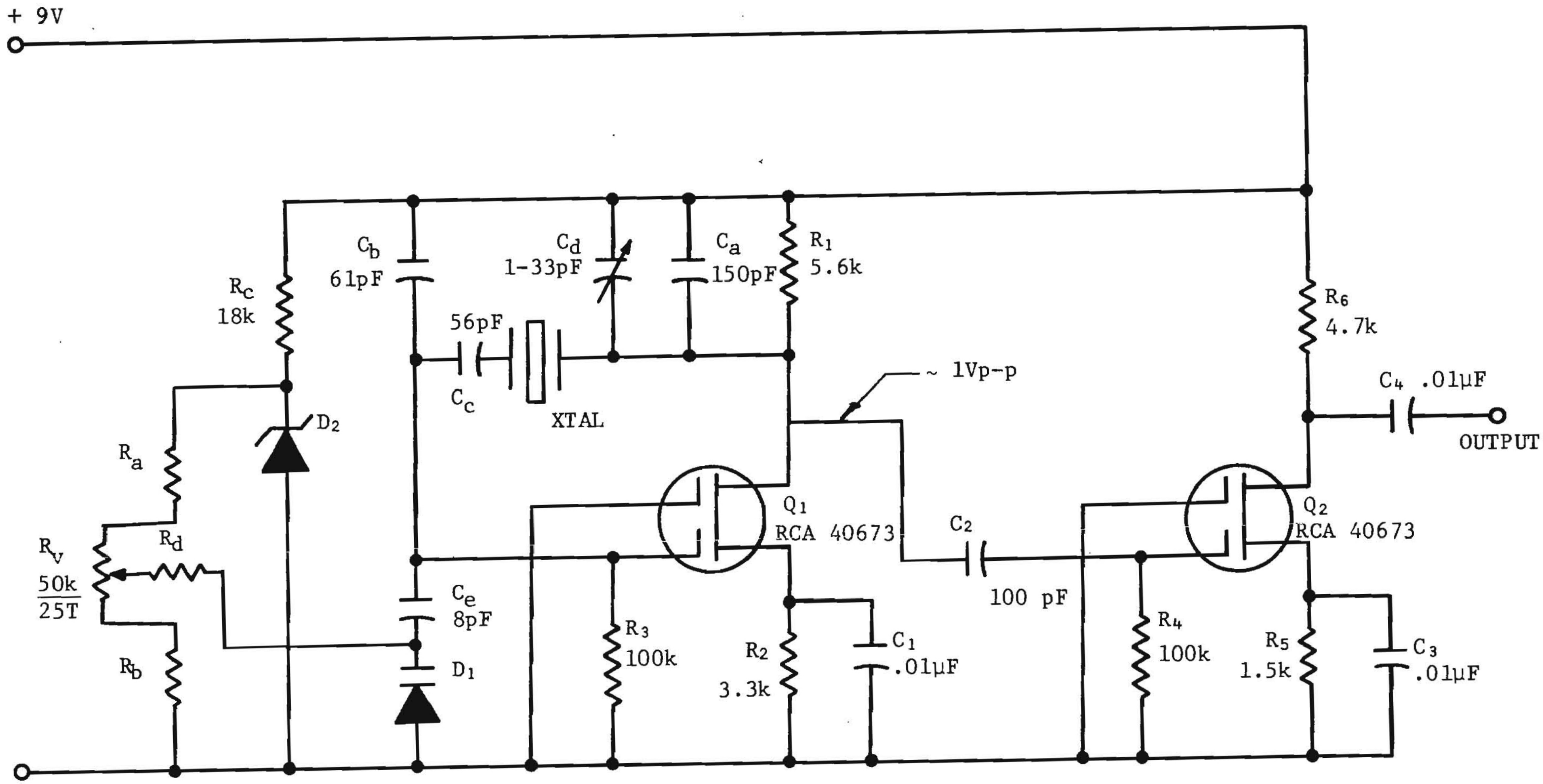
1. Oscillator Design and Performance

The performance of MOSFET type transistors, when compared with that of bipolar transistors, make them desirable for oscillator applications. In particular, the RCA Type 40673 is attractive for hybrid circuit applications because it has diode protected gates which allow handling the device with normal procedures. The tetrode, or dual gate, configuration of the 40673 allows circuit design of a much simpler nature but without compromising performance features such as automatic gain control.

The MOSFET crystal controlled oscillator circuit diagram appears in Fig. 6. It consists of an oscillator stage, buffer stage, and fine 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. Course tuning is accomplished with this capacitor, which changes the frequency ($\Delta f/f$) approximately 2 X 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 X 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 uA without loss of zener action. An input voltage of + 9V is supplied from the regulated DC supply.

After coarse adjustment of frequency to within ± 1 X 10^{-8} of 5 MHz, final tuning to ± 1 X 10^{-10} of 5 MHz is accomplished by the frequency adjustment potentiometer Rv. 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



R_a, R_b, and R_d selected for final frequency adjustment.

Fig. 6. Circuit diagram of the MOSFET Crystal-Controlled Oscillator.

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 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

$$C_s = \frac{(8.2)(80)}{8.2+80} = 7.437 \text{ pF}.$$

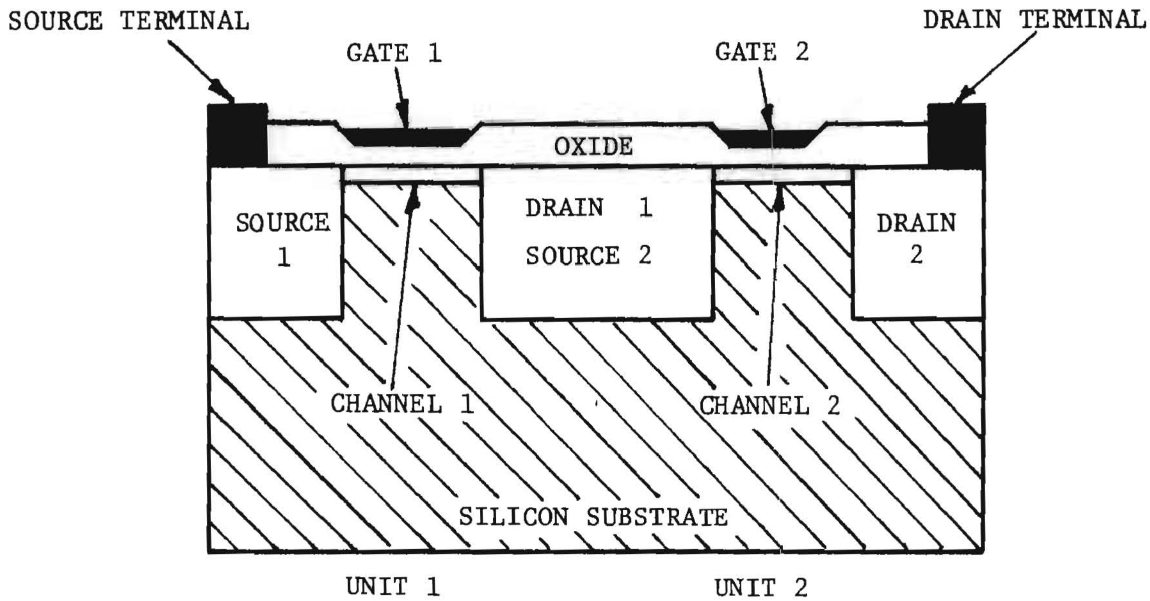
When D_1 is changed to 85 pF the capacitance, C_s, becomes 7.478 pF and ΔC_s = 7.478 - 7.437 = 0.041 pF, which is approaching the desired value.

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 ±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 is a 25 turn adjustment from end to end, then a single turn should cause a $\Delta f/f$ of approximately 8×10^{-10} or $1 \times 10^{-10}/45°$ of shaft rotation.

Automatic gain control (AGC) on both the oscillator and buffer stages can be described with the aid of Fig. 7. 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, 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 ohms. Other performance data obtained from the breadboard model of this oscillator are: (1) Frequency/Voltage Stability of about 1.2×10^{-11}/mV change in input voltage and without input regulator or tuning diode, D_1; (2) Frequency/Load Stability of less than 1×10^{-11} for ±10% change in load; (3) input power to oscillator is 10 mV, and (4) crystal dissipation is between 3 and 10 uW depending upon the R_s value of the crystal.

In an aging test at 85 °C the breadboard model obtained an aging rate of



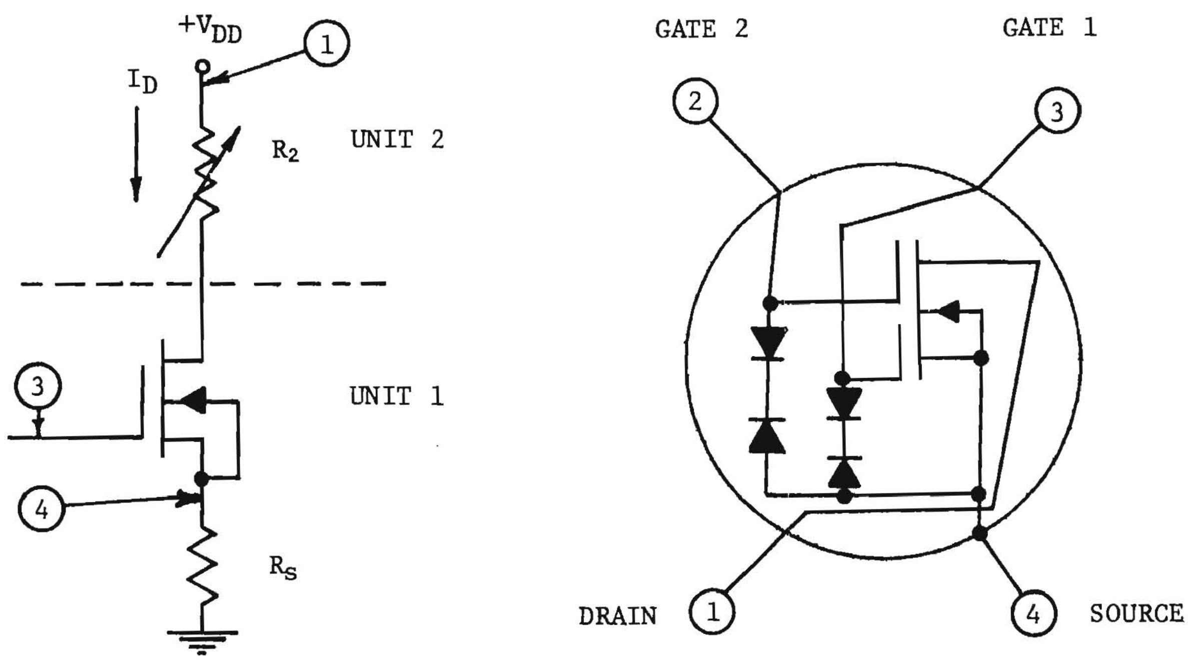


Fig. 7. Equivalent circuit representation of the two units in a dual-gate MOSFET.

less than 2 X 10^{-10} per hour, after a 24 hour stabilization period, using an in-house crystal. The breadboard is constructed with standard resistors and other components and their stability at 85 °C is believed to be poorer than the components used in hybrid oscillator circuit. Also, the circuit is assembled on a perforated glass-epoxy board which is believed to induce a strong, initial positive frequency drift when used at high temperatures.

2. Temperature Control Circuitry and Performance

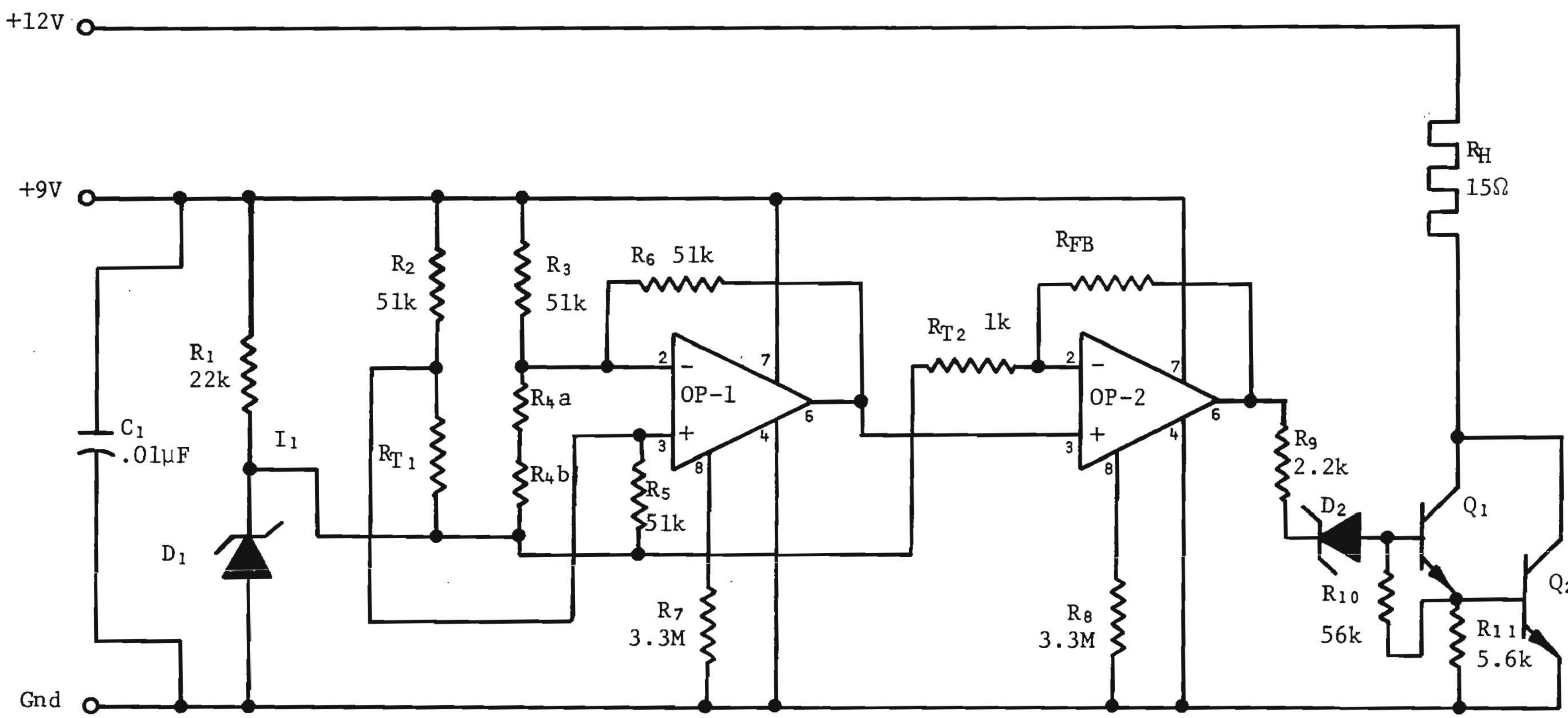
A very stable temperature is required by a crystal oven which is part of a reference oscillator. When the quartz resonator is designed for fast warmup by the inclusion of helium within the holder, the problems are magnified due to the extreme temperature sensitivity of the resonator. In the present fast warmup application, the oven must not only supply heat quickly and with precise control but also consume less than 250 mW of electrical power, after initial warmup.

Figure 8 is the schematic diagram of the proportional temperature control circuit being developed for the miniature crystal reference oscillator. It consists of a bridge sensing network, a bridge buffer amplifier (OP-1), a driver amplifier (OP-2), and power control circuit (Q_1, Q_2 and R_H). The operational amplifiers are Fairchild type uA776 and were specifically chosen for their extremely low power consumption. Input current to the control circuitry is 130 uA during the warm-up period and this current decreases to 60 uA after the warm-up period.

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 ± 1 X 10^{-7}. The thermistor was replaced with a fixed resistor of 1000 ohms.

The control circuitry operates from the regulated + 9V supply while the power circuitry operates from the unregulated + 12VDC 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 D_2 (4.5 V) prevents the output of OP-2 from driving Q_1 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 $\pm$ 4.5 V described above. When the bridge becomes unbalanced, the output from OP-2 increases and D_2 conducts, applying drive to Q_1.

Transistors Q_1 and Q_2 are connected in a Darlington configuration and provide a gain of approximately 30. Transistor Q_2 will be mounted on top of the crystal holder as described previously. During development of the breadboard control circuit this transistor could not be mounted on the holder because of the epoxy type encapsulation and its associated thermal mass.



OP-1, OP-2 : μA776

D_1, D_2 : MZC4.7B1 MOTOROLA

R_{T_1} : VECO THINISTOR TYPE FN1A6

R_4 : TRIM TO SET TEMPERATURE

Q_1 : MOTOROLA UNENCAPSULATED TRANSISTOR MMCS2222

Q_2 : MOTOROLA UNENCAPSULATED TRANSISTOR MJC082

Fig. 8. Schematic diagram of temperature control circuit.

In the final circuit configuration this transistor must be in contact with the crystal holder. After the initial warm-up period, Q_2 becomes the major source of heat dissipation. Because of the low input power requirements the dissipation cannot be wasted and therefore is used to supply heat to the crystal holder. As of this time the thermal system has not been tested with Q_2 in chip form and mounted as proposed in Section II.C.4.

The bridge thermistor must also be located on the crystal holder. This thermistor should be in extremely good thermal contact with the holder and have a low time constant. A thin film thermistor (Veco Thinistor) with a time constant of 75 mS will be used.

Figure 9 illustrates the results of four experiments* which show the effect on warmup of component location. The transistor is an encapsulated type and the thermistor is a bead type with a 2 sec time constant. These two components were used throughout the development of the thermal system. The locations used to obtain the data given in Fig. 9a were with both the control transistor (Q_2) and thermistor (R_{T1}) attached to the top of the can. Both thermistor and transistor were assumed to be in good thermal contact with each other. The heater element was wrapped around the sides of the HC-6 holder and held in position with a band which also served as heat sink. Figure 9 was obtained when the thermistor and heater were attached to the side of the holder, and the control transistor, Q_2, mounted on a separate heat sink. For Fig. 9c, thermistor and heater were again attached to the side of the HC-6 holder and the control transistor remotely located. However, the heater and thermistor were in good thermal contact but not the heater and holder. For Fig. 9d the thermistor was attached to the top of the holder. Both the thermistor and heater made good thermal contact with the holder. The control transistor was again located on a separate heat sink.

The heater power in each of these four cases was 5.4 W. The control transistor resistance is about 5 Ω when saturated. The heater resistance is 15 Ω. During warmup the input current to the power circuitry is 600 mA, therefore heater power during warmup is $P = I^2R = (600 \times 10^{-3})^2 (15) = 5.4$ W and maximum power input to power circuit during warmup is $P = (600 \times 10^{-3})$ $(12) = 7.2$ W. The input power usually switches from its maximum in about 16-20 seconds from turn-on at room temperature. Note that in none of these initial warm-up and temperature stability experiments was the heated crystal insulated as well as the crystal will be in the final assembly.

Figure 10 shows two warm-up curves in which all variables were kept constant except thermal loading due to the alumina circuit boards. The bead thermistor was bonded to the top edge of the HC-6 holder and the whole crystal-heater-thermistor assembly was enclosed in polyurethane foam. Other system parameters are indicated on the graph. The frequency was measured at one minute intervals beginning one minute after turn-on. The plots do not indicate the overshoot which occurs during the first minute.

The added mass of the alumina circuit boards decreased the degree of overshoot/undershoot of the system and the frequency offset at one minute was improved by a factor of two. Thus, it appears desirable to have as much thermal mass in the system as can be heated to the operating temperature in the allowable time of one minute. The larger thermal capacity will also aid

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*The crystal unit used for this and the following experiments was in an HC-6 holder filled with 30 torr of He.

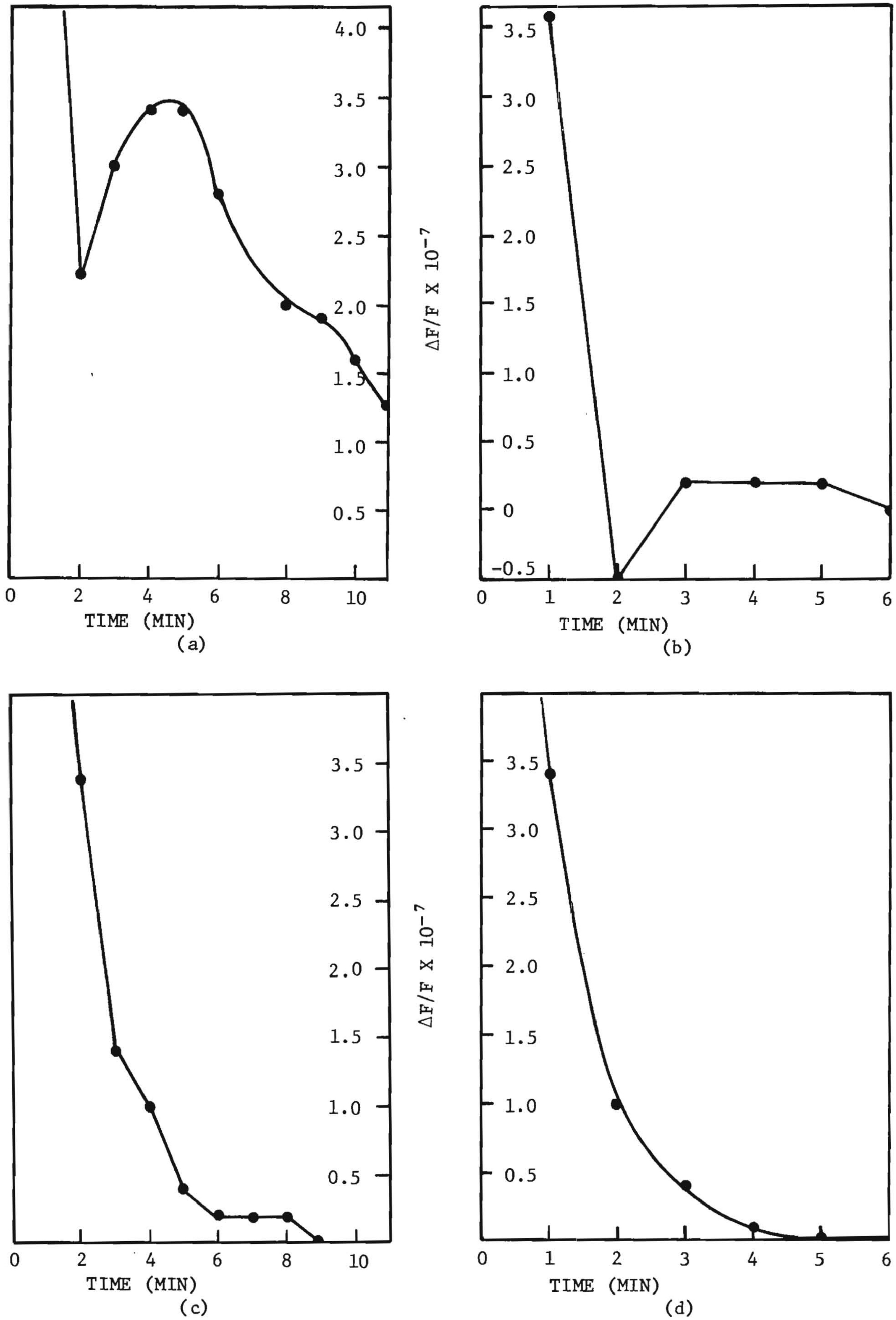


Fig. 9. Effects of component location on warm-up characteristics.

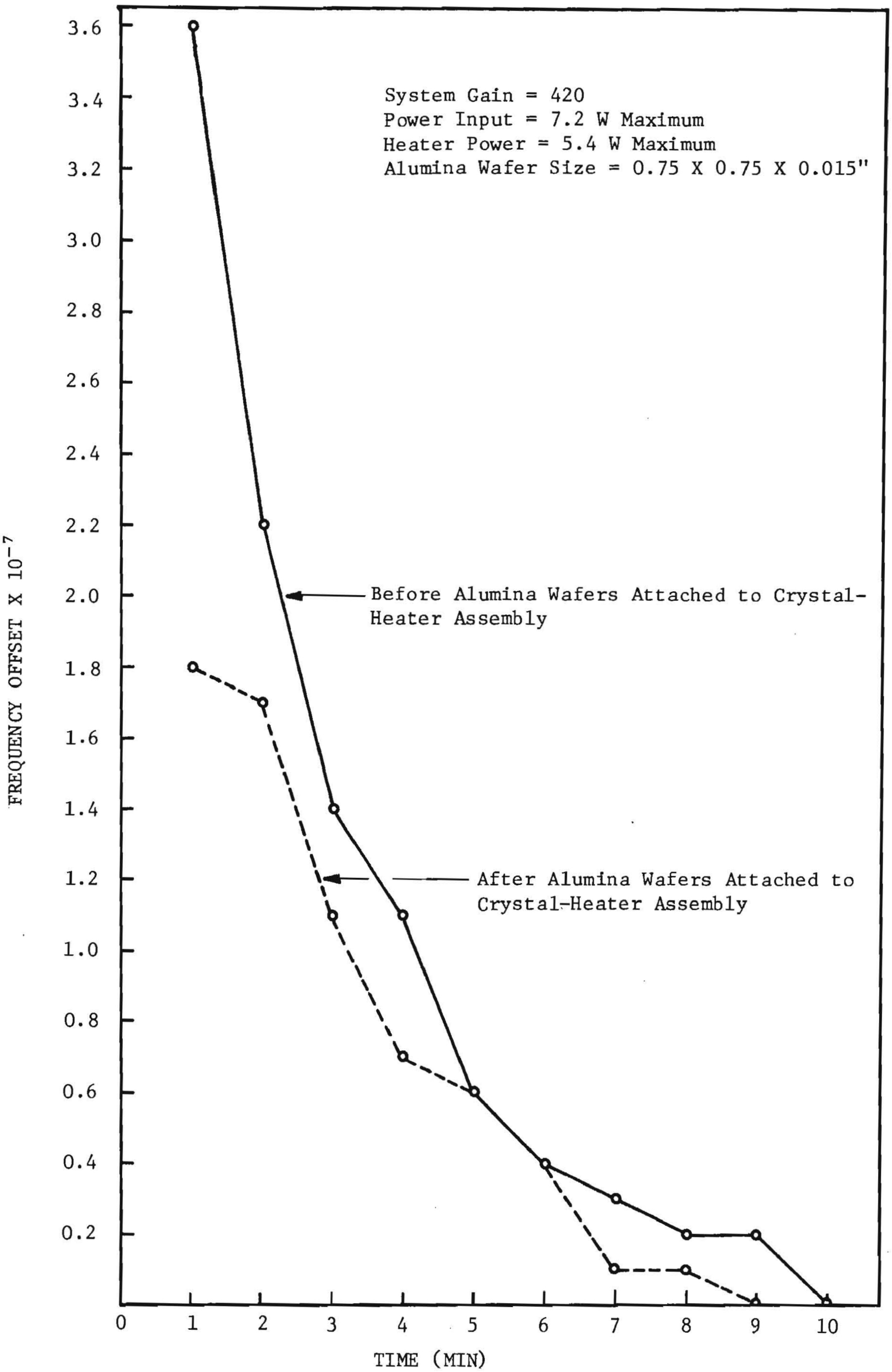


Fig. 10. Effect of thermal loading on warm-up characteristics.

the short-term temperature stability. Note that after the first minute the frequency offset in each case is not significantly different.

In Fig. 11 the family of curves show the effect of system gain on the warm-up characteristics. All other variables, such as power input and thermal insulation were held constant during this experiment. The frequency offset after one minute shows an increase in a positive direction with an increased system gain. At the higher gains the system bandwidth becomes smaller and the full power input remains on longer. The temperature overshoot is thus high and the power is reduced to almost zero. The temperature falls rapidly and full power is applied again for a shorter period of time. This combination of power input and system gain results in a temperature stabilization period which is longer than desired. At the lower gains the bandwidth is too large and the heater power is reduced too soon. The temperature drops rapidly and is still low at the end of one minute. At gains between approximately 60 and 200 the frequency offset is within $\pm 1 \times 10^{-7}$ of the reference frequency after one minute from turn-on. In this range of system gain the power input is reduced at a rate which minimizes the temperature overshoot and undershoot. Notice how the differences between the curves at two minutes through ten minutes become less, indicating very little dependence on the gain of the system. To understand this process better, another experiment was performed and the results are shown in Fig. 12. Here the system gain was held constant at about 200 and the effect of adding thermal insulation to the thermistor was investigated. The thermal insulation consisted of a small block of polyurethane foam cemented directly on top of the thermistor. The frequency offset after one minute was essentially unchanged after adding the insulation, verifying its dependency on power input and system gain, assuming a constant value of heater thermal insulation (air in this case). After two minutes, the frequency offset could be reduced 30 percent by reducing the thermistor heat loss and correspondingly reducing the system power. Bonding a thin-film thermistor to the holder with a thermally conductive epoxy adhesive, such as Delta-Bond 152, should lower the frequency offset still further. In addition, the final assembly will be sealed in vacuum and surrounded with NRC-2 insulation. The convection and radiation losses will therefore be virtually nonexistent and the thermistor will sense the temperature of the holder and not the surrounding environment. Data shown in Fig. 13 were obtained under similar conditions to those shown in Fig. 11, except the thermistor was insulated in polyurethane foam. Note scale change for $\Delta F/F$ in Fig. 13. This figure indicates that with a gain of around 100 the frequency offset requirement is met at one minute. With the additional thermal insulation and improved thermal contact of heater, thermistor, and crystal holder in the final model the frequency offset requirements at two, four and fifteen minutes should be met.

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 will be 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 set 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 temperature

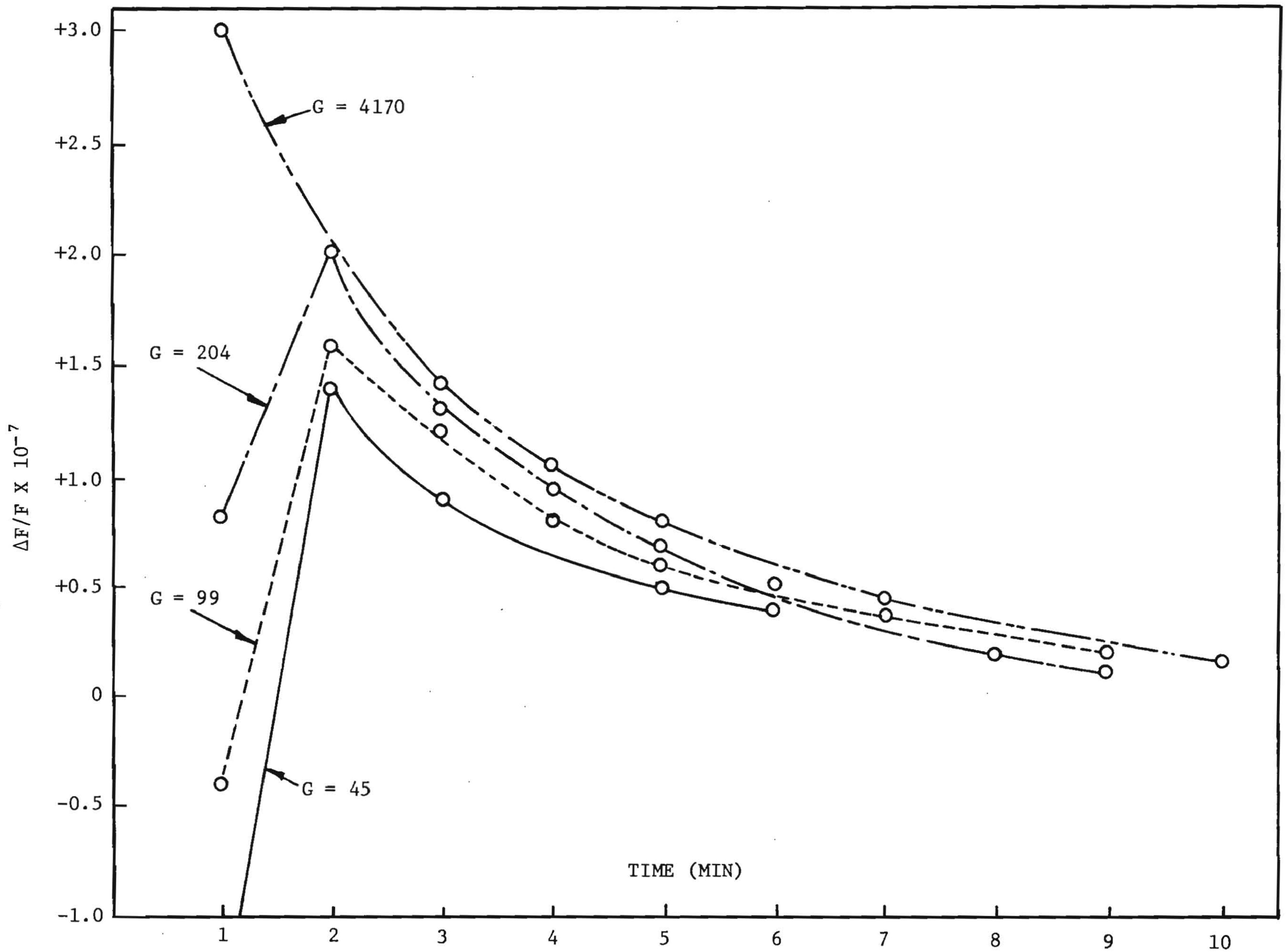


Fig. 11. Effect of system gain on warm-up characteristics.

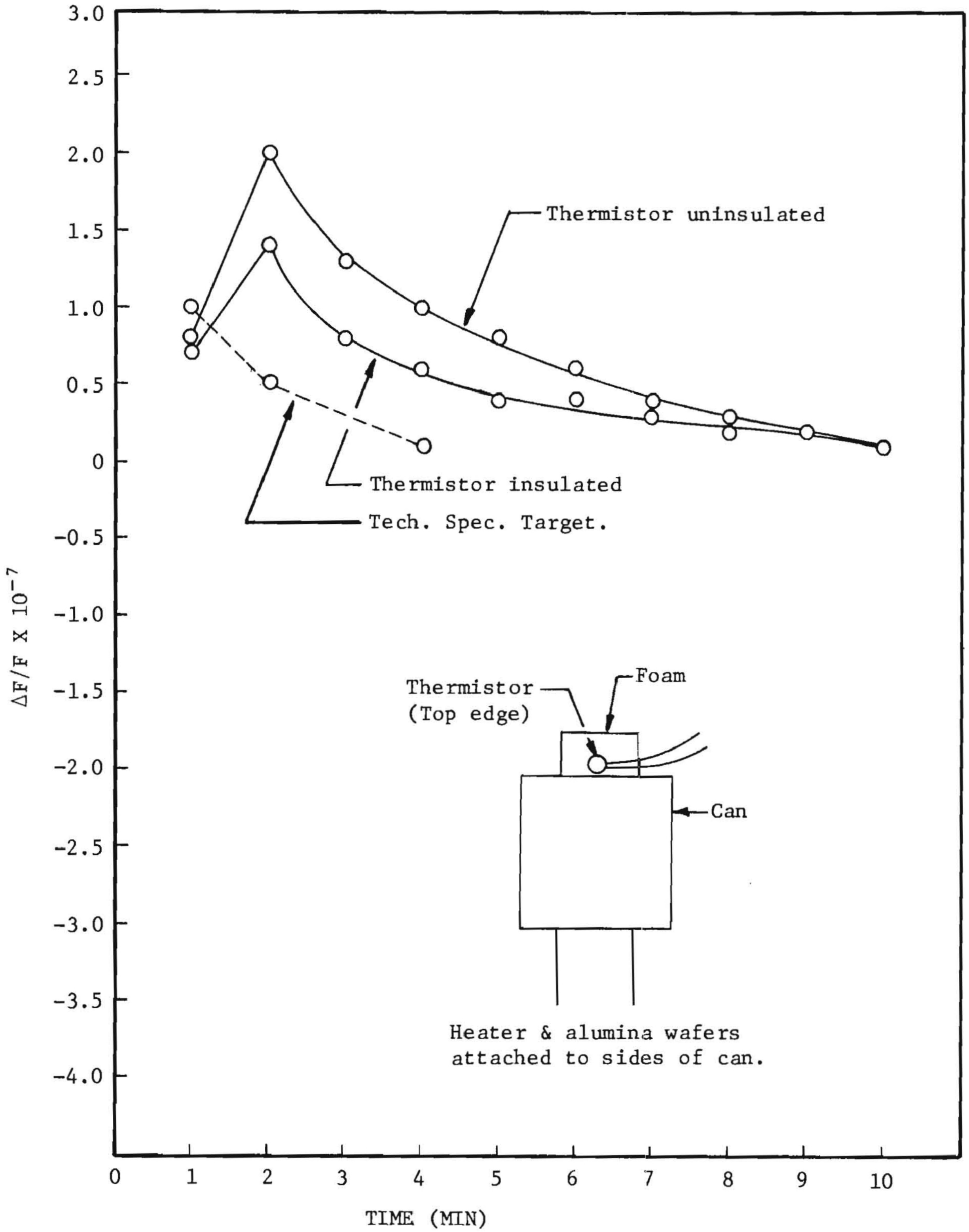


Fig. 12. Effect of thermistor insulation on warm-up characteristics.

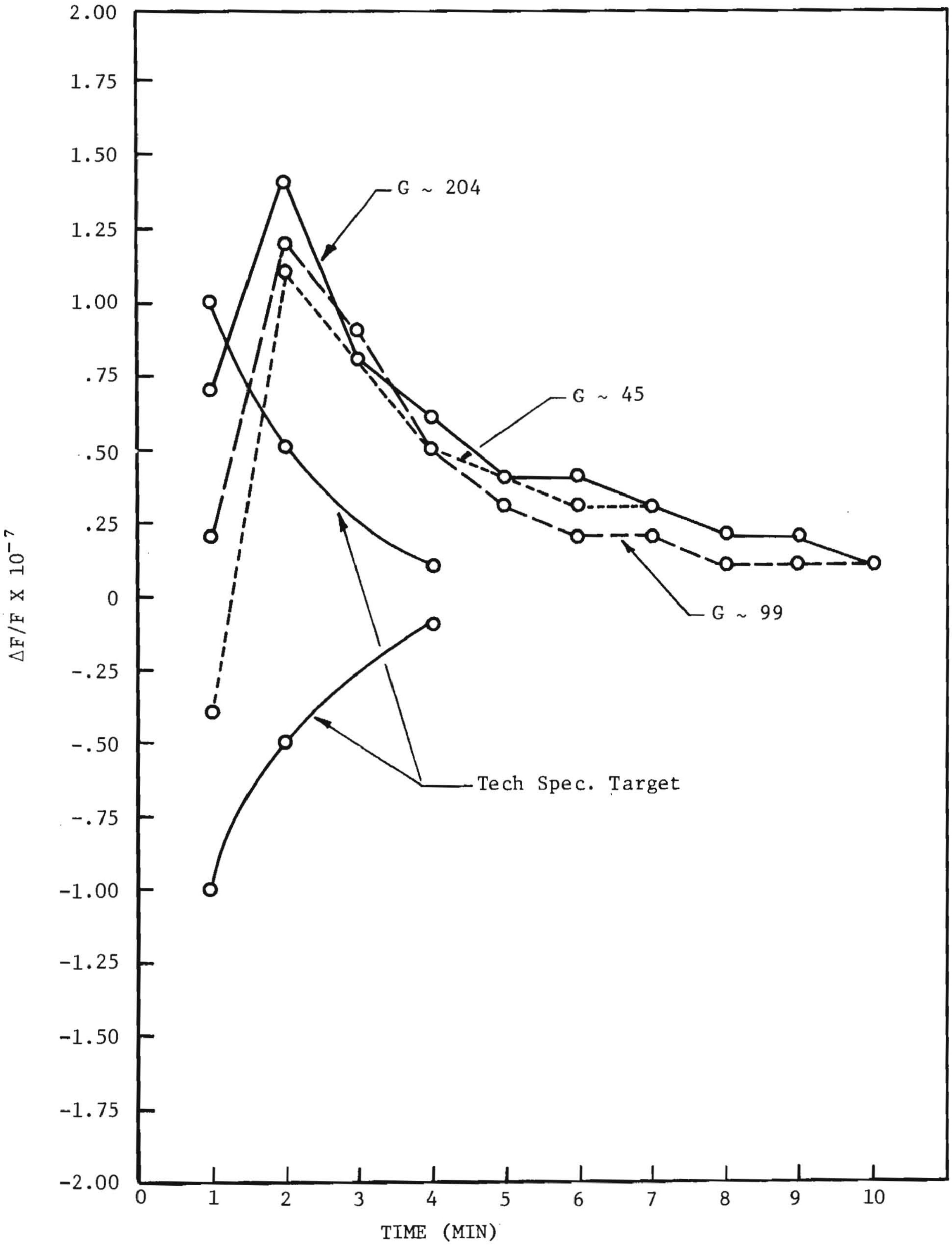


Fig. 13. Effect of system gain on warm-up characteristics with thermistor insulated.

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 R_{4a} and R_{4b} (see Fig. 8) sets the temperature. Resistor R_{4b} in the final circuit configuration is a Motorola type MMCR100-025 which can be varied in steps of 25 Ω from 25 to 2750 Ω. After the operating temperature has thus been adjusted, the crystal is connected to the oscillator circuit and the oscillator tuned to the final frequency as previously described.

3. Voltage Regulator and Performance

A voltage regulator is required to provide the operating voltage for the oscillator and temperature control circuits. This regulator must be located outside of the isothermal region because of thermal mass limitations, and thus must exhibit very good output stability over the temperature range of -40 °C to +75 °C. In addition, the regulator must be small and require few external components.

The Fairchild type μA723 voltage regulator appears to meet these particular demands. It is supplied in a TO-5 package and only requires four additional components. 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 ±5% of 0.01% of the output voltage. The change in output voltage of Fig. 14 over an input voltage range from 11.4 to 12.6 V is less than 1 mV.

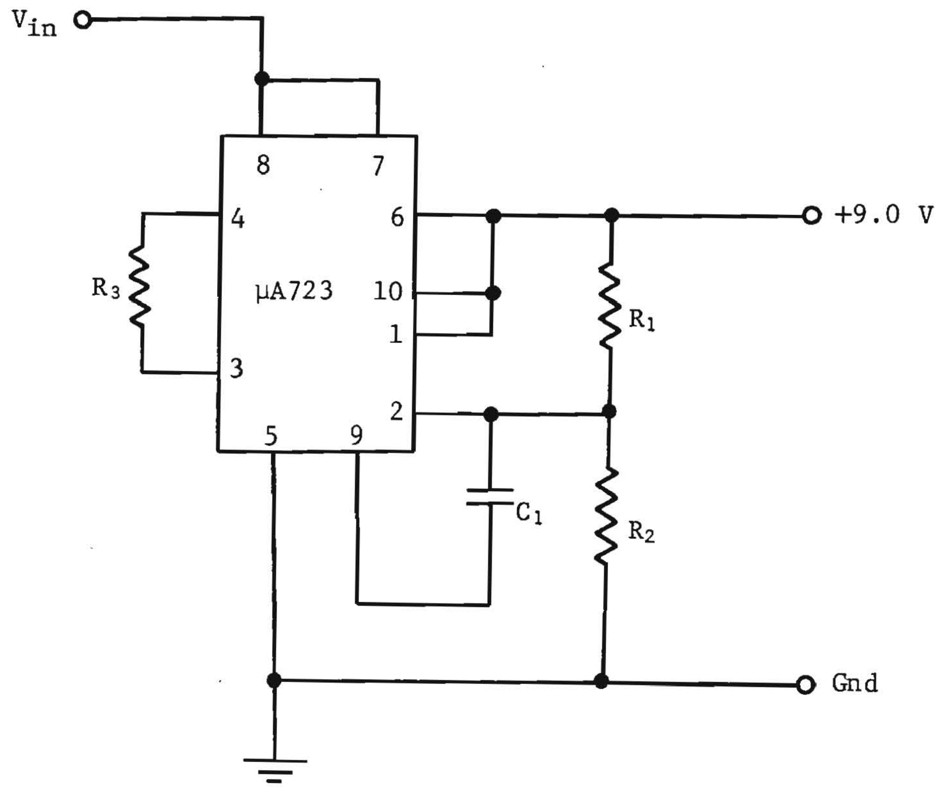
Figure 15 illustrates the degree of output voltage stability over the ambient temperature range. Data below 1 °C have been extrapolated. Between 1 °C and 75 °C there is a 11 mV change in output voltage. If this regulator configuration does not provide the necessary voltage/temperature stability, an external reference voltage zener for the regulator can be located in the isothermal region. Such a configuration will certainly improve the temperature coefficient of the regulated +9 V, but at the expense of running two more wires between the isothermal region and the type-D base.

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 type μA723 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 all connections were soldered, 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 type-D base of the main unit with epoxy adhesive.

4. Microcircuit Fabrication

This section discusses fabrication of the MOSFET oscillator-buffer and temperature control circuits. Hybrid techniques were employed for both circuits. Apparatus and facilities available were discussed previously in Section II.B. Several problems ensued during our initial fabrication efforts; most of these were solved or systematically eliminated. It is expected that



R_1 : 1.5kΩ/1/8 W
R_2 : 6.8kΩ/1/8 W
R_3 : 1.5kΩ/1/8 W
C_1 : 100 pF
V_{in} : 12 V ± 5%

At 12 V input and load current of 1 mA the power input is 30 mW.

Fig. 14. Schematic diagram of voltage regulator circuit.

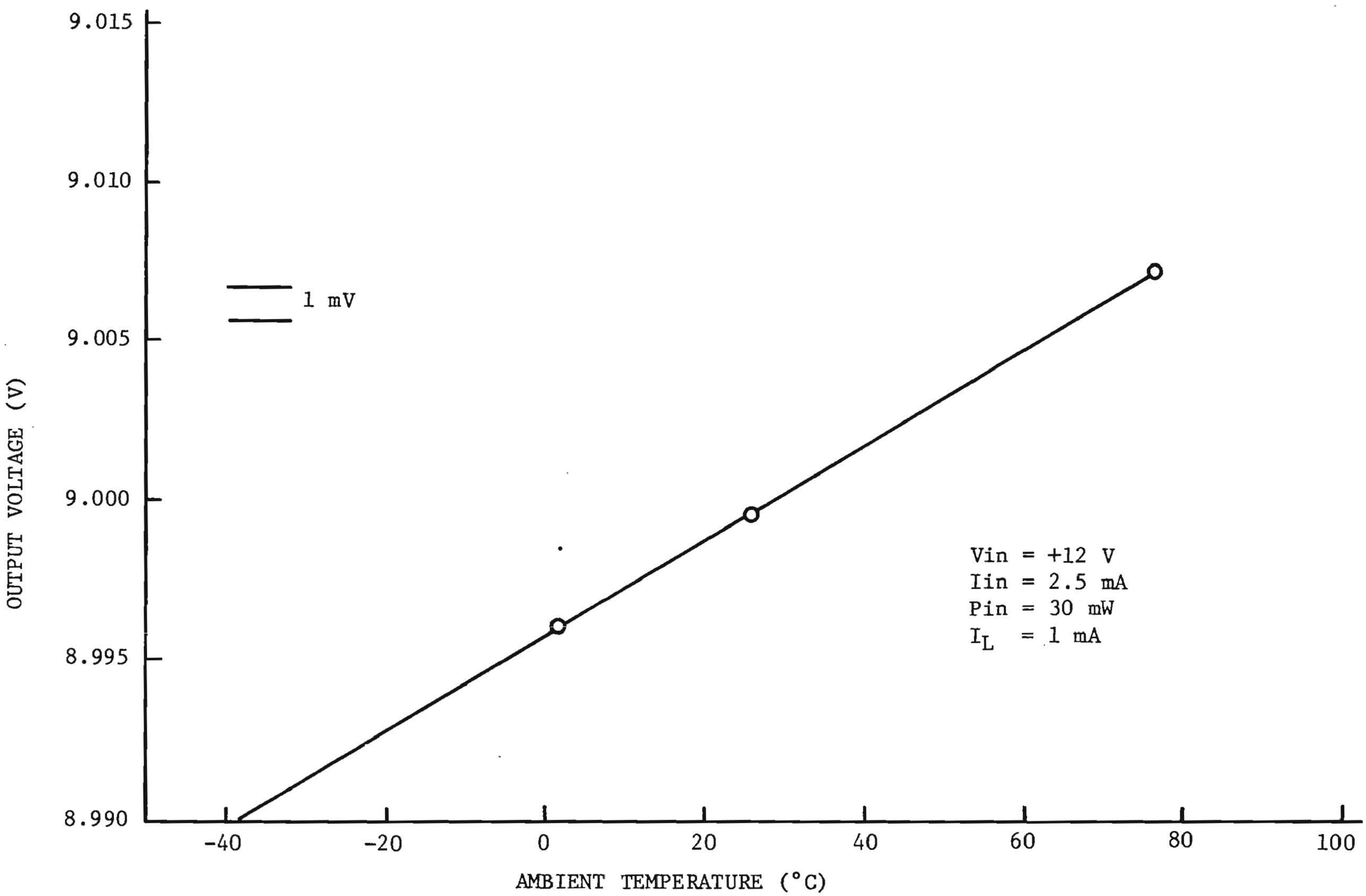


Fig. 15. Output voltage vs temperature for voltage regulator.

the few remaining problems can be solved with minimal effort.

4.a. Substrates

High purity alumina (99.5% Al_2O_3, American Lava type #772) was selected as the substrate material for the oscillator circuit and for a major portion of the control circuit. Dimensions of the alumina substrates are .5" X .625" X .015". Two such substrates are required--one each for the oscillator circuit and temperature control circuit. These substrates lay flat on the sides of the HC-6 crystal holder, leaving approximately 1/8" clearance at the top.

The control transistor and thermistor of the temperature control circuit, both of which require good thermal contact with the crystal holder, are mounted separately. Because of its high thermal conductivity, beryllia* (99.5% BeO, American Lava type #754) was selected as the substrate material for the control transistor. It is planned to die bond the control transistor to a gold pad on a beryllia chip and then secure the chip to the crystal holder with epoxy adhesive. Dimensions of the beryllia chip are .25" X .115" X .025". As discussed previously in Section II.D.2, the thermistor will be adhesively bonded directly to the crystal holder. Figure 16 shows the relative position of the control transistor chip to the substrate of the temperature control circuit.

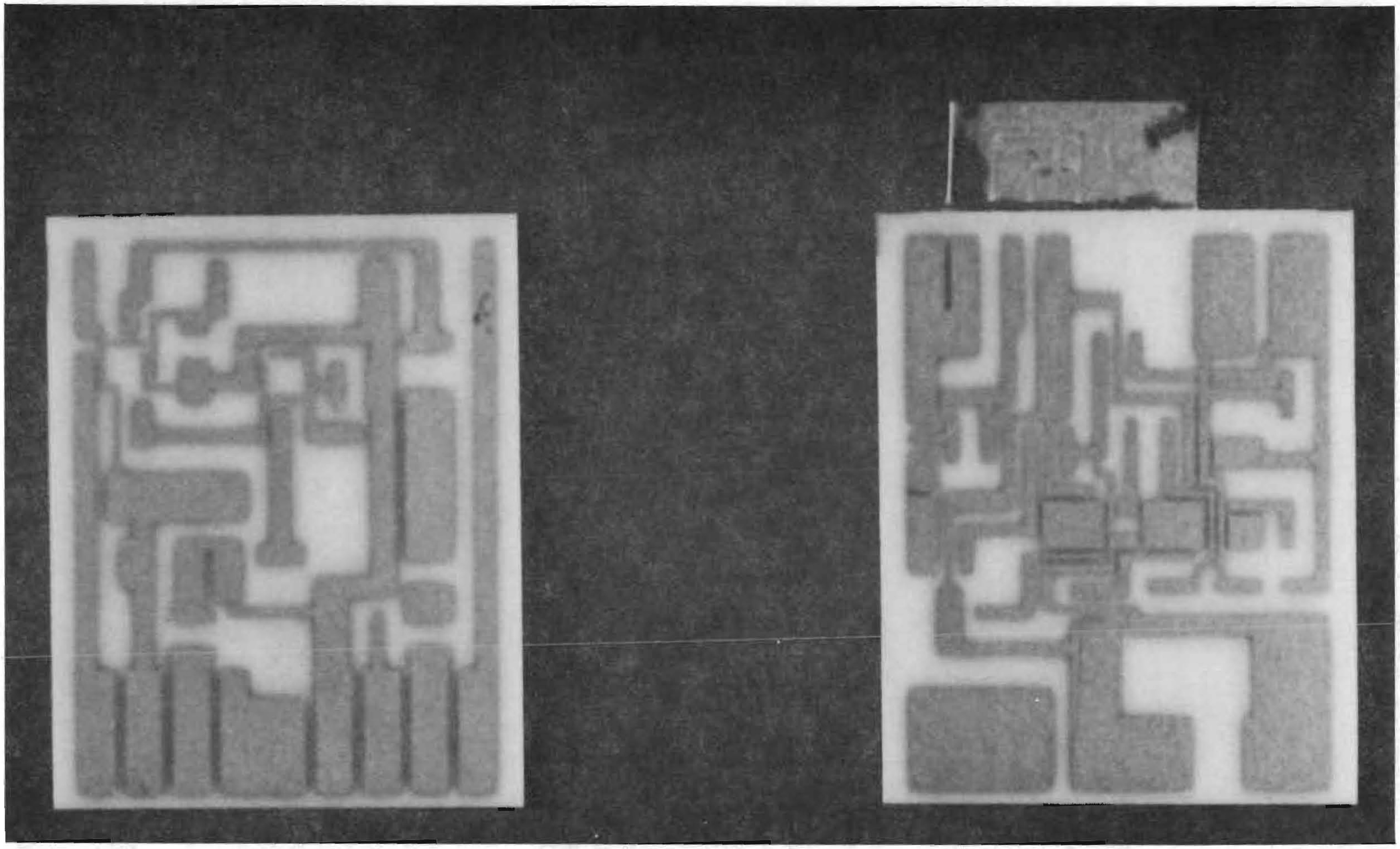
All substrates were used in the as-fired conditions; i.e., the substrate surfaces were not mechanically polished. The manufacturer specified the as-fired finishes as 8 and 18 micro-inches for the alumina and beryllia surfaces, respectively.

4.b. Fabrication of the Conductor Pattern

Photographs of conductor patterns for the MOSFET oscillator-buffer and temperature control circuits are shown in Fig. 16. Film conductors are gold over chromium. The gold film consists of 5000 A of evaporated gold plus a final 3 microns of electroplated gold. A thin layer ($\simeq$ 1000 A) of chromium was evaporated immediately before the evaporated gold without breaking vacuum to enhance adherence of the gold to the substrate. The entire front surface of the substrate was plated with the gold over chromium film prior to engraving of the conductor pattern. Circuit patterns were engraved by conventional photolithographic techniques. After engraving, the film was annealed in air at 500 °C for 15 minutes and then slowly cooled. Annealing of the electroplated gold enhanced the ability to make thermal compression wire bonds to the gold film during circuit assembly.

Meticulous cleaning methods and photolithographic techniques are required during the fabrication of micro-miniature circuit patterns. Though complex, such techniques are in common practice; thus, the extensive details involved are purposely omitted. However, detailed methods similar to those employed were reported by Grismore, et al.[4]

*The American Lava Corporation, Chattanooga, Tennessee, gratiutously furnished the alumina and beryllia substrate materials.



a b

Figure 16. Microminiature circuit boards for the MOSFET oscillator and temperature control circuits. (a) MOSFET oscillator-buffer circuit, (b) temperature control circuit.

4.c. Hybrid Components and Their Attachment to the Micro-Circuit

Figure 17 is a photograph of a typical hybrid oscillator circuit assembled. Resistors† are of the flip chip variety with length and width of 0.050" and a power rating of 1/8 W. "Vee Jem" ceramic chip capacitors†† are employed, except for adjustable capacitor, C_d, in the oscillator circuit. Length and width of the "Vee Jem" capacitors are .080" X .050" for .01 μF capacitors. The resistors and capacitors were obtained with pre-tinned terminations and soldered to the gold film by reflow techniques in the first two circuits assembled. Through an error in design the film terminations for soldering R_3 were omitted in the conductor pattern. Rather than delay fabrication, R_3 was epoxy bonded to the substrate between capacitors C_1, C_c and C_e. Diodes D_1 and D_2 and adjustable capacitor C_d were obtained as silicon chips with gold backing and secured to the substrate by die bonding to the conductors which also serve as one termination. Flying gold leads were bonded by thermal compression techniques to make connection from the aluminum pads on the chips to points in the conductor pattern. The MOSFETS, Q_1 and Q_2 could not be obtained in chip form at the start of the project. To conserve space, the MOSFET chips were dismantled with leads intact from their TO-72 holders and epoxy bonded to the substrate. Some difficulty was experienced with bonding the aluminum leads of the MOSFET to the gold film as discussed subsequently.

Initially, oscillator circuits were fabricated using solder reflow to attach the resistors and capacitors. Flux was required to obtain good bonding to the gold film. The solder has two disadvantages. Firstly, too much tin-lead solder diffuses into the gold resulting in undesirable leaching of the gold film. Secondly, complete removal of flux residue is near impossible by the limited cleaning techniques available after the components are mounted. It is feared that the flux residue will result in undesirable outgassing in the final package.

To minimize the extent of alloying of the Sn-Pb-Ag solder on the pre-tinned passive components with the pure gold films, special soldering tools were machined to solder 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, i.e., slightly below the reflow temperature of the solder. Additional heat was then applied to each component in turn with the special soldering tool to accomplish the reflow. The process was observed under a microscope and the soldering tool was removed as soon as reflowing was complete. Even under these conditions the extent of alloying of the solder with the pure gold film was quite difficult to control. At best, one soldering operation was all that could be performed reliably. Since final frequency adjustment of the oscillator is accomplished by removal and substitution of selected values of several of the resistors, it was apparent after a few trials that the gold films would not withstand multiple soldering operations with the solder supplied on the pre-tinned components.

Leads have been soldered, removed, and resoldered several times to the gold films using CERROSEAL solder* which does not require a flux.The composition

†The flip chip resistors were purchased from Mini-Systems, Incorporated, North Attleboro, Mass.

††The chip capacitors are the "Vee Jem" type manufactured by Vitramon, Incorporated, Bridgeport, Conn.

*Product of the Cerro Corporation, New York.

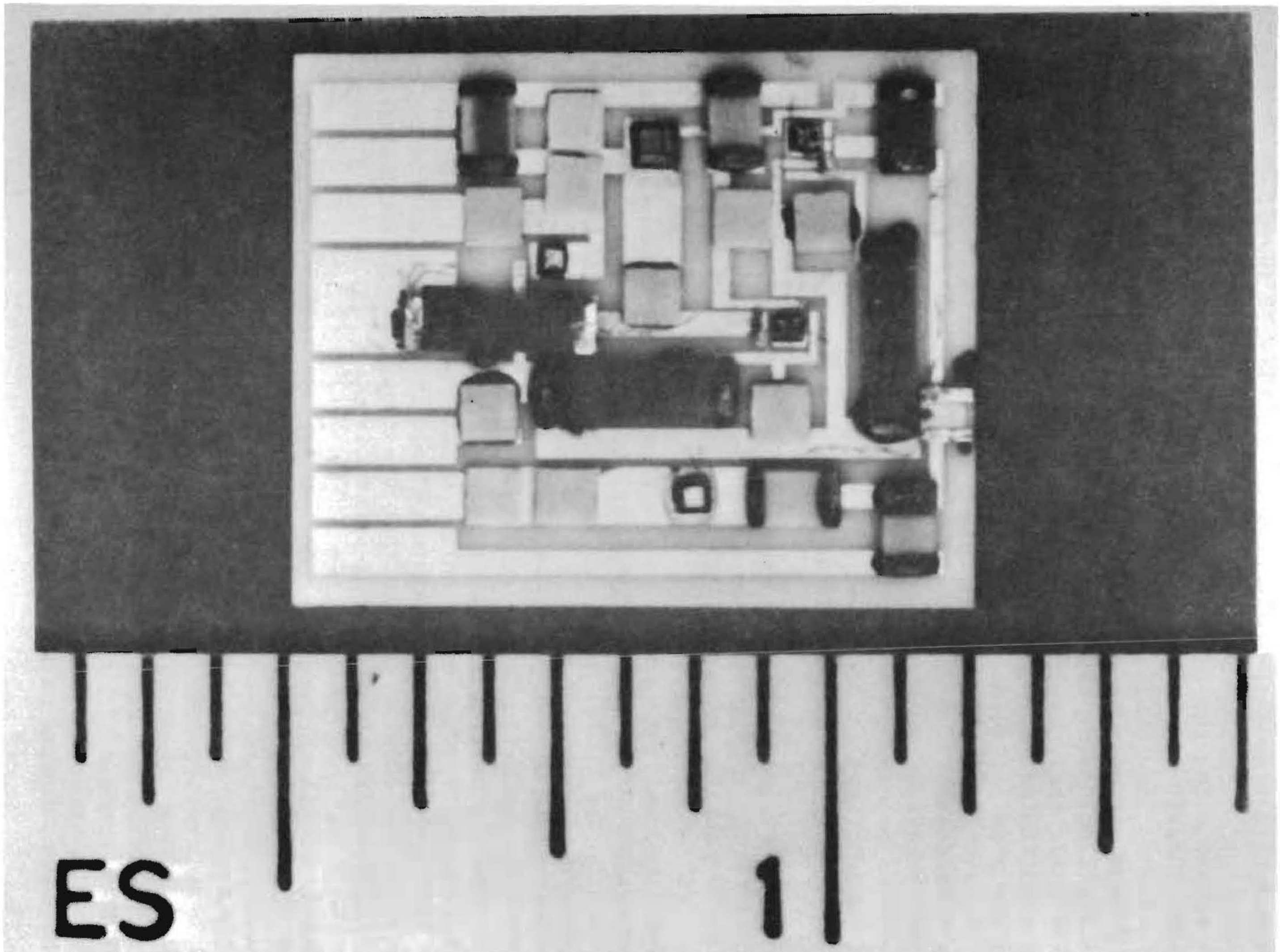


Figure 17. Photograph of hybrid oscillator circuit.

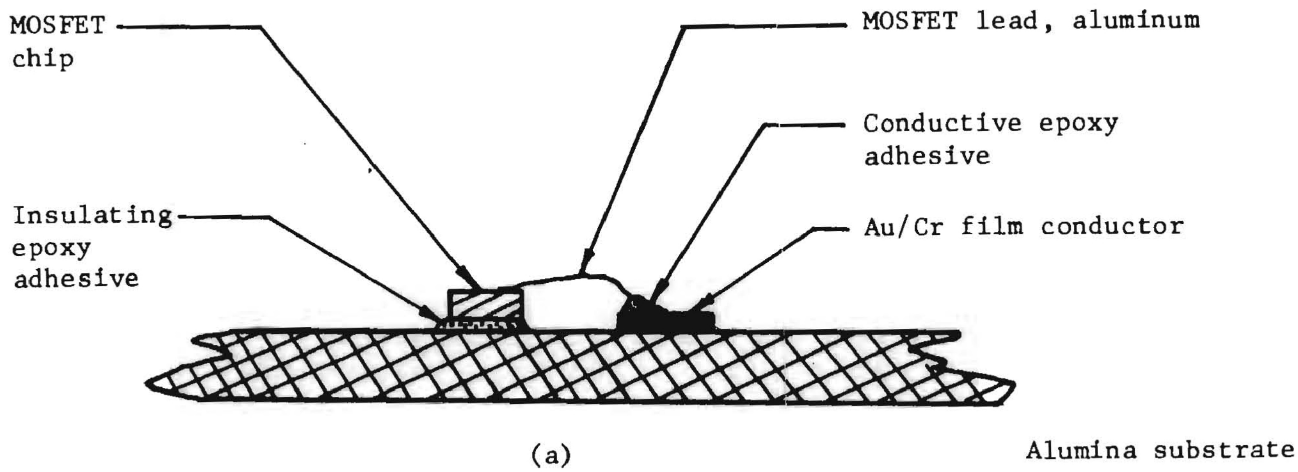
of this solder is a non-eutectic alloy consisting of 50 wt.% tin and 50 wt.% Indium, with a melting point of 120 °C. Apparently, the lower melting point contributes to the good soldering properties when used with gold. In the future, it appears desirable to use this type of solder where soldering is required. Further experimental work with CERROSEAL solder on chip components is required before a definite decision can be made regarding its usefulness for attaching chip components to gold films.

After experiencing the difficulties associated with reflow soldering of components to gold films, circuits were assembled using conductive epoxy adhesive to secure and terminate the passive components to the gold conductors. Removal of epoxy bonded components is accomplished by local heating with a small soldering tip to soften the adhesive. The component is then removed while the epoxy is in a softened state. Other components can readily be substituted and bonded in the same position. This procedure eliminated the possibility of destroying the conductors and allows final tuning of the oscillator circuit to be accomplished by selection of components by substitution. Plans are to use epoxy adhesive to terminate the passive components for circuits in the first TMXO. Typically, the oscillator circuit is mounted on a test board for preliminary evaluation of circuit performance and to determine the approximate values for R_a, R_b, R_d, and R_{d_2} before their attachment to the microcircuit chip.

As stated previously, we were initially unable to purchase MOSFETS in chip form. In order to meet minimum space requirements, the encapsulated MOSFET chips we obtained through a local supplier were dismantled from their containers with leads intact. It was soon discovered that the chips are easily damaged and we lost several in the dismantling process. Difficulty has also been experienced in obtaining reliable bonds between the aluminum leads attached to the MOSFET chips and the gold film conductors by either TC or ultrasonic bonding. In order to obtain reliable bonds, the aluminum leads were positioned and tacked to the gold film with a TC Wedge bonder, then secured with conductive epoxy adhesive. Microscopically rough surfaces on the gold films, a characteristic of such films on alumina substrates, appear to be a primary contributor to the bonding problem. Since aluminum wire bonds were readily made to evaporated gold films on optically polished glass and quartz surfaces it appears that the topographical condition of the gold can significantly affect bonding properties.

The hybrid oscillator has been bench tested at temperatures ranging from 25 °C to 90 °C. Performance was as good as the breadboard model in similar tests. However, some component values required changing from the values in the breadboard model. Values of C_b and C_c were changed from 82 to 62 and from 68 to 56 pF, respectively, to adjust the feedback to gate 1 and load capacitance to the required value. The value of R_6 was changed from 2.7 kΩ to 4.7 kΩ to increase the gain of the buffer stage. Apparently, the gain of the MOSFETS decreased after their removal from the TO-72 holders. Also, the difference in stray capacitance between the breadboard and microcircuit forms may have contributed to the required changes of component values.

Initially, intermittent operation of the oscillator-buffer circuit was experienced during bench tests. This was traced to two possible sources involving the leads on the MOSFETS. The leads on the MOSFETS as disassembled from their holders are slightly short for bonding into the conductor pattern. This has resulted in some leads passing so close to the edge of the semiconductor chip that shorting can occur, see Fig. 18a. Also, it has been noted that occasionally the epoxy adhesive does not readily wet the aluminum leads.



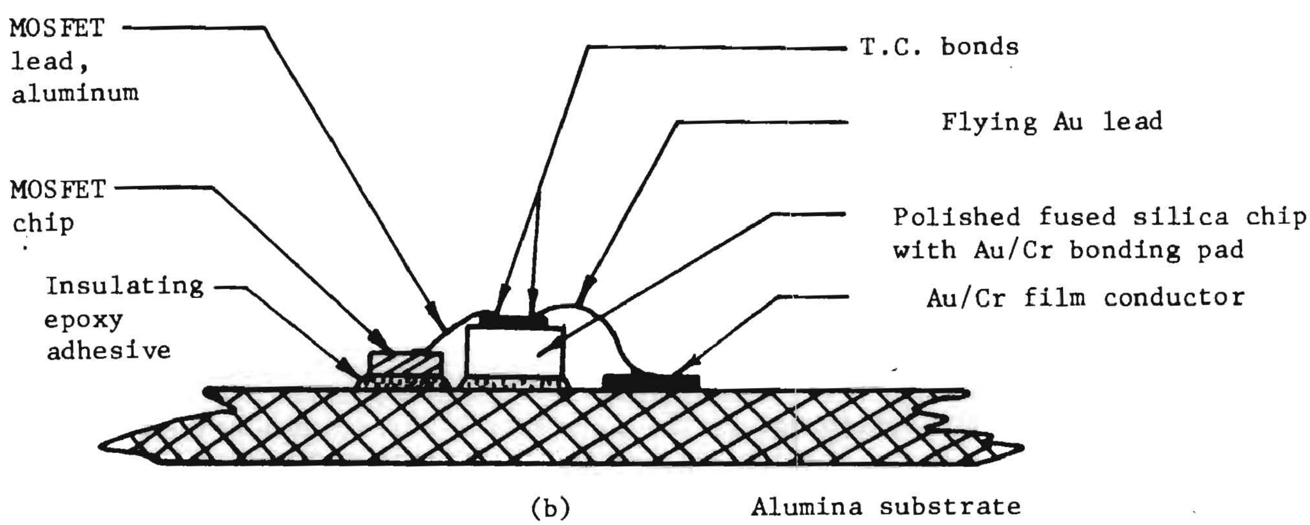


Fig. 18. Sketch illustrating attachment of MOSFET chip to microcircuit board; (a) initial manner of attaching MOSFET chip to circuit board, (b) modification of attaching MOSFET to eliminated shorting of leads to edge of chip.

There is some indication that the latter has resulted in several high resistance terminations. A modification to hopefully eliminate these possible troubles is illustrated in Fig. 18b. The plan is to evaporate a gold/chromium film onto optically polished fused silica substrates. The plated substrates will be diced to form small chips with gold bonding pads. The chips will be epoxy bonded to the alumina substrates adjacent to the MOSFET chips in order to provide raised bonding pads for the MOSFET leads. This will eliminate the possibility of shorting of the MOSFET leads. In addition, the better bonding characteristics of gold films on the polished surfaces will possibly allow the aluminum leads to be TC bonded.

A delay in delivery of the operational amplifiers has in turn delayed completion of the temperature control circuit. Delivery of the amplifiers is expected soon. Plans are to secure all active components by die bonding to gold pads on the substrate and to make circuit connections with flying gold leads. The passive components will be terminated and secured with conductive epoxy adhesive having low outgassing properties.

5. Concluding Discussion

Breadboard models of oscillator and temperature control circuits have been developed and their performance evaluated.

The oscillator circuitry is simple in design but incorporates automatic gain control and electronic fine tuning. The simplicity of the design is appealing when conversion to microcircuitry is desired. The performance of this design has been such that the technical guidelines pertaining to oscillator performance should be met.

Development of the temperature control circuit included investigations regarding the locations and method of attaching the control transistor (Q_2) and the thermistor (R_{T1}), which in addition to circuit gain, have an appreciable influence on the fast warm-up characteristics of the quartz resonator.

The voltage regulator is a commercially available item and the design of this circuitry was straightforward. The regulator's performance has been investigated and it is believed to be sufficient to meet the requirements of the oscillator and temperature control circuits.

In general, satisfactory processes for fabricating the microcircuits have been developed. Delivery holdup of the operational amplifiers for the temperature control circuit has caused at least a 30 day setback in our schedule for completing the first TMXO. Once the operational amplifiers are received the microcircuit fabrication for the first TMXO is expected to be completed in a matter of days.

E. Reliability and Quality Tests

1. Crystal Units

The quartz resonators used in the oscillator are commercially obtained units with the specifications as outlined in Section II.C.2.

Five units were purchased and subjected to preliminary aging tests, frequency/temperature tests, and warm-up tests.

Figure 19 shows the frequency change versus the time in days at 85 °C for the five crystal units. Unit 6 exhibited the lowest aging of the five units and was chosen to be used in the first prototype TMXO.

Frequency/temperature tests were performed on all units to determine their UTP temperature. Each unit was immersed in an oil bath and the bath temperature increased slowly from room temperature through the UTP temperature. The resonator was driven with a TS-330/TSM crystal impedance meter and the frequency measured with a counter. The UTP temperature of each was approximately 89 °C which is 1 °C higher than the specification tolerance. Figure 20 is representative of all five units.

Fast warm-up tests were only performed on Unit 6. The first test involved immersing the crystal in a preheated oil bath set at 89 °C. The unit was driven with the Cl-Meter and the frequency measured with a counter and recorded, after D/A conversion, on a T-Y recorder. After approximately 10 seconds the frequency had decreased to a value about 17 Hz below the UTP frequency. Between 20 and 60 seconds the frequency returned to the UTP frequency measured previously at 89 °C. The reason for this behavior during fast warmup is unknown but may be due to stress which is introduced by thermal gradients.

Unit 6 was fitted with a heater element as described in Section II.C.4 and the heater connected to the temperature control circuit. Frequency was measured with a synthesizer driven crystal bridge at one minute intervals from power application to the heater. The bead thermistor was attached temporarily to the HC-6 holder with silicon rubber. The data resulting from this test compare closely with the data from previous units tested under similar conditions. It is believed that the behavior observed during the oil bath warmup will not present any problems.

2. Vibration

No vibration testing has been performed on the first prototype oscillator model as yet. Vibration testing has been done, however, on test models fabricated for this purpose. These test models used identical components to those being used to construct the first prototype.

A type-D base with a stainless steel pedestal spot-welded to it and a crystal holder spot-welded to the pedestal platform exhibited no mechanical resonances between 5 and 100 Hz. The test method used is Method 201A, MIL-STD-202D.

Two alumina substrates the same size as the hybrid circuit boards were attached to the sides of the crystal holder, one on each side, and the assembly tested again for resonances. No resonances were observed between 5 and 55 Hz, but a strong resonance beginning at about 60 Hz and peaking at about 65 Hz was observed. This resonance occurred when the base/pedestal assembly was mounted in a horizontal position and was intense enough to break the pedestal from the type-D base.

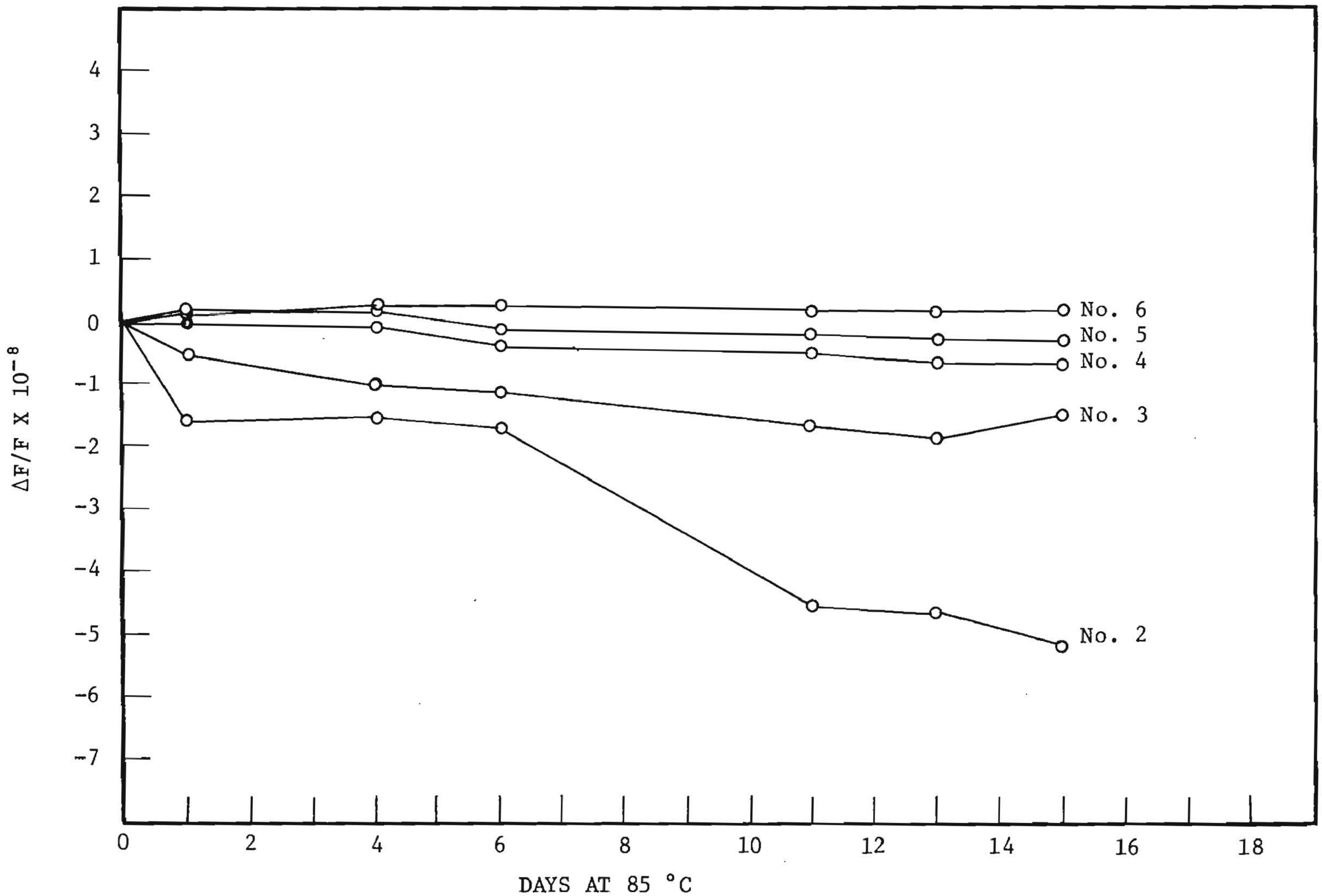


Fig. 19. Aging data for 5 MHz resonators purchased for the tactical miniature crystal oscillator.

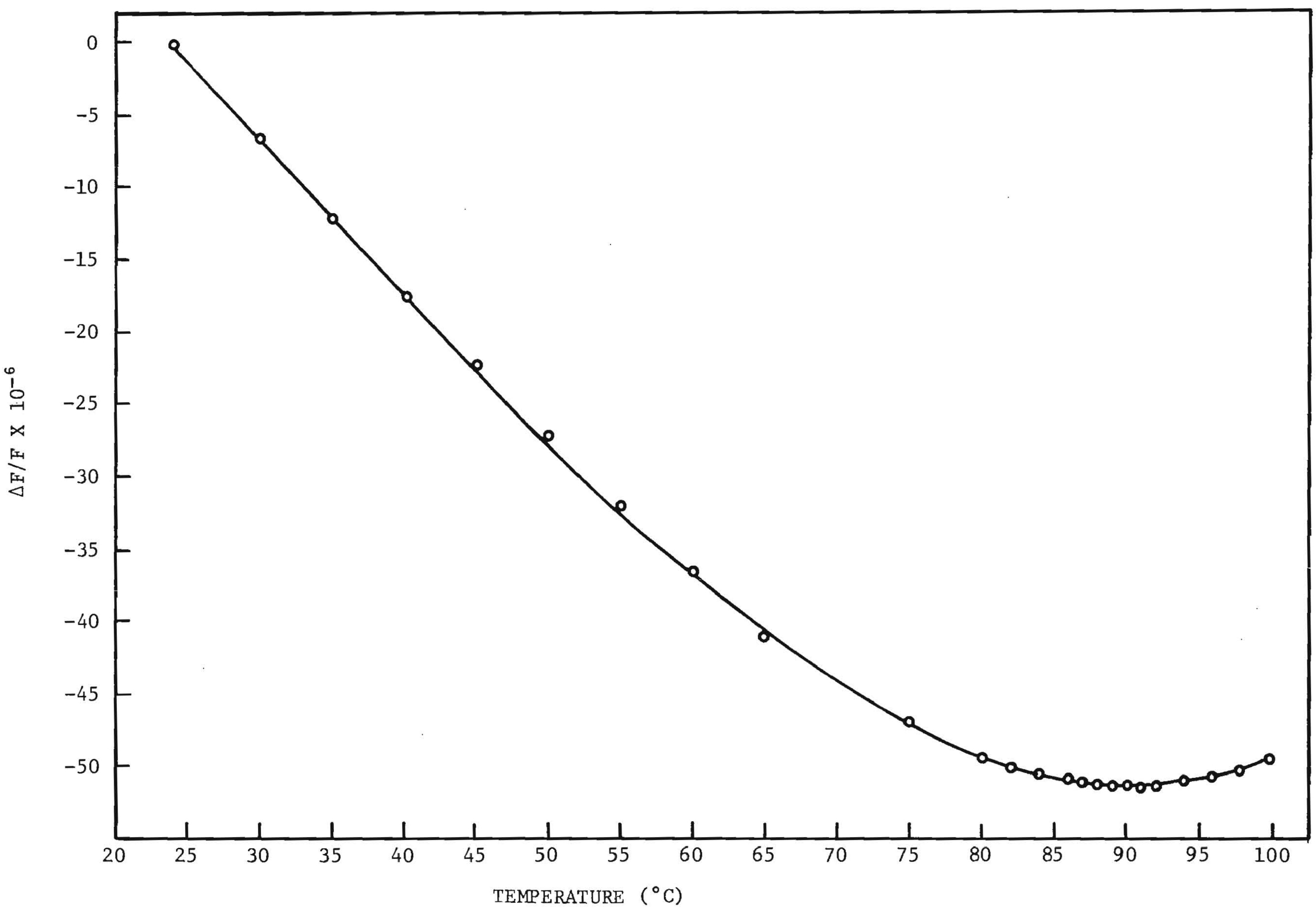


Fig. 20. Temperature coefficient of frequency of unit 6.

The crystal holder will be epoxy bonded to the pedestal in the prototype model, as described in Section II.C.4, and the pedestal base to the type-D base will be spot-welded and reinforced with epoxy adhesive. This construction should be stronger than spot-welding because of the larger mating surfaces that are bonded together between the components.

3. Discussion

Commercial crystal units were obtained and subjected to aging, UTP, and fast warm-up testing. The UTP of all units was slightly higher than desired but apparently will not present a warm-up problem. The other test results compare favorably with those obtained from experimental crystal units produced in-house and used during the early investigations of the thermal system.

Preliminary vibration tests have shown no mechanical resonances between 5 and 55 Hz are present in the basic structure. The effect of vibration on the output frequency of the completed TMXO has not, of course, been determined at this time.

III. CONCLUSION

Any conclusions to be drawn from this work will naturally be dependent on the results of the compliance tests which will be carried out on a completed prototype TMXO. Although it may be premature to judge the outcome from the present vantage point, it would appear that the construction of a TMXO to meet the rigid specifications set forth in the guidelines will be essentially met.

IV. ACKNOWLEDGEMENT

The considered help of M. D. Carithers and L. A. Phillips in the preparation of this report is recognized. The experimental work has been principally the work of Mr. Carithers and Mr. Phillips, especially during the past few months. The past contributions of L. C. Young, H. W. Denny and C. S. Wilson are also recognized.

The help given by 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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3 ABSTRACT

The purpose of this work is to design and construct exploratory development models of a fast warmup 5 MHz tactical miniature crystal oscillator (TMXO). The total package is to be contained within a volume not to exceed 5 cubic inches, operate in an ambient temperature range of -40 to 75 °C with a maximum permissible frequency deviation of $\pm 1 \times 10^{-8}$. Available power to heat the temperature sensitive elements of the TMXO from ambient to 85 °C in one minute is 10 watts; operating power after warmup will be limited to 250 milliwatts. An output frequency deviation, after a 30 day stabilization period, of less than $\pm 2 \times 10^{-10}$ per week is required, as well as a short term stability of $\pm 1 \times 10^{-11}$ for periods of time ranging from 1 sec to 20 min. To conserve space and power, both the oscillator and temperature control circuits are of the hybrid microcircuit variety. An encapsulated frequency adjustment potentiometer is provided with the adjustment control accessible from outside the hermetically sealed oscillator.

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Microcircuits						
Fast warm-up						
Low power						
Low aging						
Minimum retrace						

CONTRACTOR EVALUATION REPORT (UNCLASSIFIED) ON

TACTICAL MINIATURE CRYSTAL OSCILLATOR (MODEL NO. 1)

PREPARED BY
RAYMOND K. HART

AUGUST 1972

ECOM

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

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SUMMARY

The equipment evaluated in this report is a Tactical Miniature Crystal Oscillator (TMXO). This 5 MHz oscillator was designed to include such features as 1) rapid warmup, 2) low operating power over a 125 °C ambient temperature range (-40 to +75 °C), 3) low long-term aging, 4) excellent short-term stability, and 5) minimum frequency retrace due to the intermittent operation. The physical size of the device (which will deliver at least 0.125 Vrms across a suitable load) is limited to five cubic inches.

The performance data contained in this report was obtained from tests which were made in accordance with the Technical Guidelines of Contract No. DAAB07-71-C-0301. 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 warmup time, operating power, frequency, stability, etc.

The pertinent data obtained for TMXO Model No. 1 is as follows: a) operating voltage range is 11.4 to 12.6 Vdc; b) maximum warmup power is 7.8 W; c) operating power is 625 mW at -40 °C, 360 mW at 24 °C and 150 mW at 75 °C; d) power aging not measured; e) ambient temperature range tested was -40 °C to +75 °C; f) frequency adjustment is $\pm$ 1.5 X 10^{-7} (3 X 10^{-7} end to end); g) frequency/temperature stability between -40 °C and +75 °C is 7.4 X 10^{-7}; h) frequency/load stability for a load deviation of 1000 Ω ± 20° is -2.2 X 10^{-9}; i) frequency/voltage stability for an input voltage variation of 11.4 to 12.6 V is -1.4 X 10^{-9}; j) frequency aging requirement not met with crystals used; k) 4 X 10^{-10} for 10 second sampling time; l) frequency/warmup characteristics below specification - see text; m) frequency recovery at -40 °C ambient is 7.8 X 10^{-9}; n) output voltage is 177 mV rms across 1000 Ω load; o) complete TMXO not tested for shock. Mechanical resonance of pedestal assembly is above 55 Hz.

These data from TMXO Model No. 1 do not generally meet the technical specifications. Some of the most important requirements such as power, frequency, stability other than long term aging and warmup time were not achieved. Certain design changes are indicated by the results of these tests and suggested changes are described in the text.

TABLE OF CONTENTS

PERFORMANCE EVALUATION OF TMXO MODEL NO. 1

I. INTRODUCTION

The technical guidelines for the development of a Tactical Miniature Crystal Oscillator call for a fast warmup OCXO to be developed with a proportional temperature control encapsulated in a hermetically sealed enclosure and with the maximum use made of integrated circuitry techniques.

The first development model being evaluated in this report comprises a 5 MHz fundamental mode resonator in a helium-filled hermetically sealed can, heater, hybrid oscillator and temperature control circuits, all enclosed in the isothermal region of a thermally insulated enclosure.

The relevant technical data and specifications 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.

II. TESTING 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 warmup 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. 1 and 2 respectively. Figure 1 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 standards and external standard for Hewlett-Packard Model R360A computing counter. The in-house secondly 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

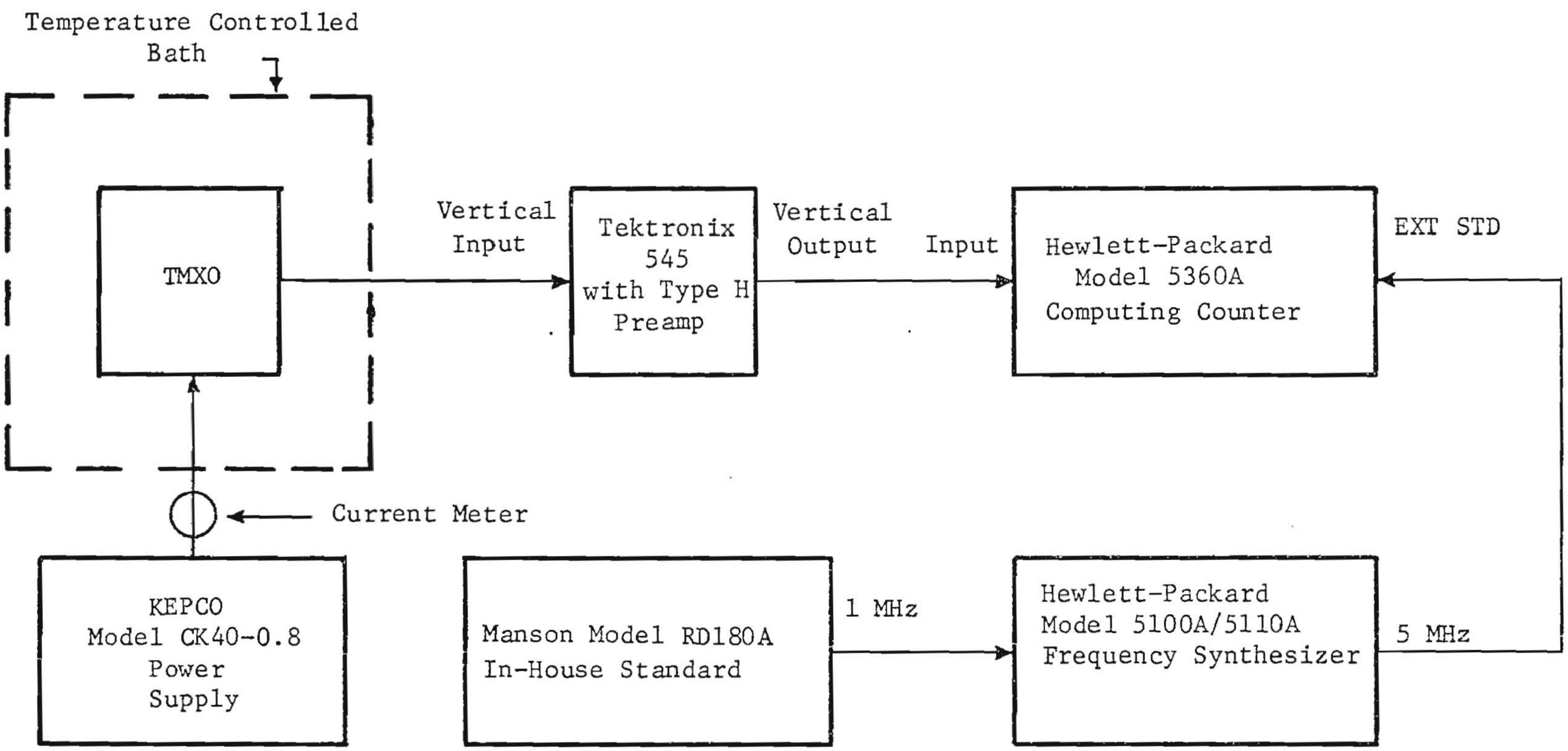

Fig. 1. System for the measurement of warmup time, warmup power and the frequency during and after warmup. Frequency readout is digital.

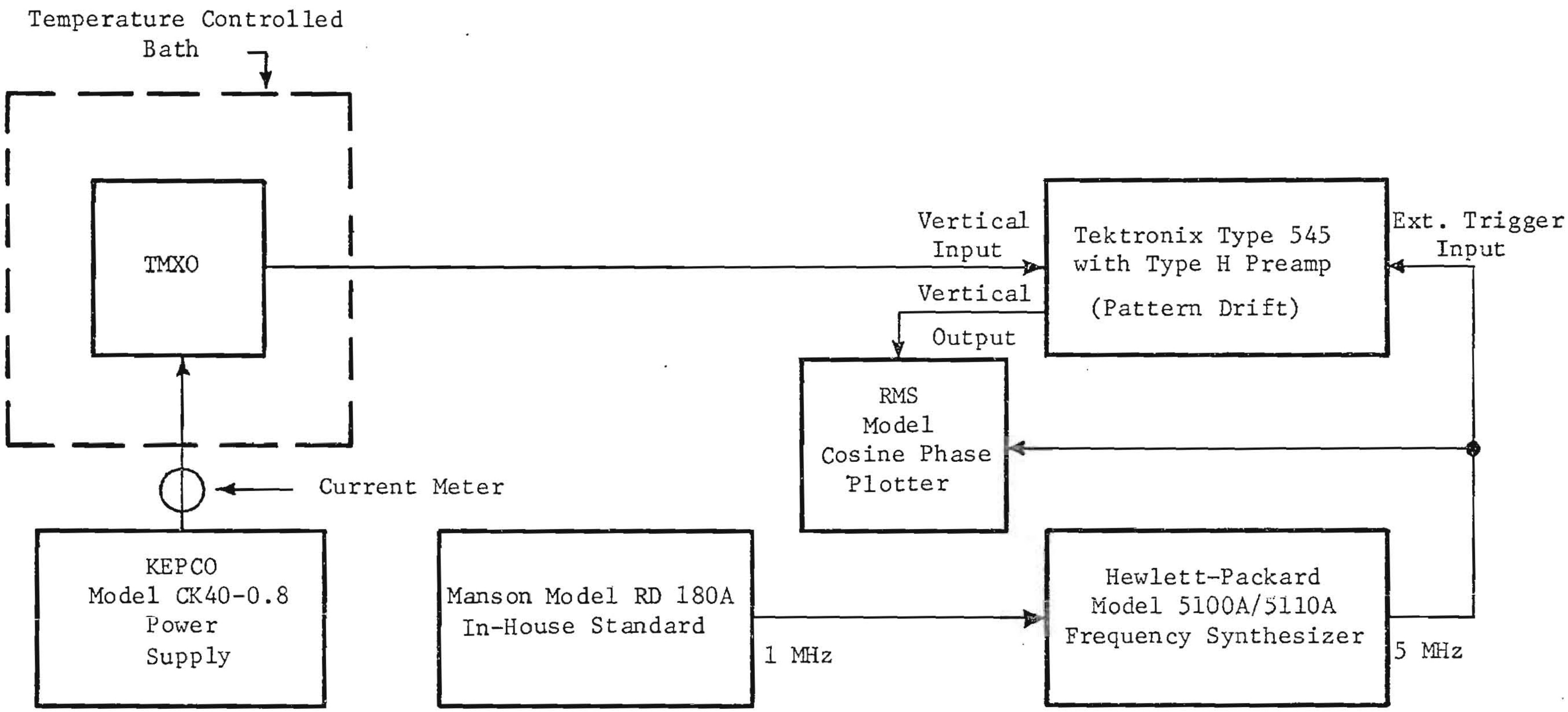

Fig. 2. Alternate system for making performance measurements. The frequency readout is analog. This method especially suited for long periods of operation with equipment unattended.

Division of the Engineering Experiment Station. The system shown in Fig. 1 was used mainly for short-term measurements i.e., 1 second to 60 minutes. The other system shown in Fig. 2 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 warmup; ripple, less than 0.5 mV rms.

The current flowing from this power supply to the TMXO unit was monitored by a 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 vibramatic system (MB Electronics, division of Textron Electronics Incorporated, New Haven, Connecticut) 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 Tektronic 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.

III. RESULTS OF EVALUATION TESTS

A. Introduction

After TMXO Model No. 1 was completely assembled and sealed by cold-welding it was discovered (by power consumption) that the can was not vacuum tight. The leak appeared to be caused by a series of diffusion-type pass between the metal and glass fill in the base. The cold-weld die was also found defective and required additional grinding work done on it.

After a telephone discussion with the Contractor's Technical Representative (Dr. E. Hafner), it was decided to fabricate a new base for this unit from stainless steel and hard solder in three high temperature electrical feedthroughs. This base was then soldered to the can with CERROSEAL-35 (Sn-In Solder). This change in our method of fabrication necessitated using a pumpout line since the stainless steel base could not be cold-welded to the can. Permission was received from Dr. Hafner to carry out the evaluation test with the TMXO being continuously pumped with an 8L/S ion pump. The base pressure during testing was 5×10^{-8} torr.

B. Volume

The volume of the extended type-D cold-weld holder enclosing the TMXO is 4.8 cubic inches. Adding the pinched-off tubulation to this figure the total volume is 4.9 cubic inches. Although this is under the 5 cubic inch specification the two succeeding experimental units will have a volume of approximately 4.5 cubic inches. This slight decrease is due to a modification of the can structure.

C. Power Requirements

1. Operating Voltage

All tests except where specified otherwise were carried out at a nominal operating voltage of 12 V dc. The actual operating voltage range is 11.4 to 12.6 V dc (12 V ± 5%).

2. Warmup Power

The full power of 7.8 W (set by heater resistance) was applied during warmup for 70 sec at -40 °C, 30 sec at 24 °C, and 10 sec at 75 °C. These values represent 546, 234 and 78 W-sec respectively. The guidelines warmup power specification is 10 W for 60 sec (600 W-sec) at any temperature. The power consumed, measured in W-sec (joules), over a 15 min period starting at turn-on is shown in Fig. 3. The technical guidelines permit 810 W-sec for the first fifteen minutes. The actual power consumed as shown in Fig. 3 is 1168, 837, and 385 W-sec for ambient temperatures of -40 °C, 24 °C, and 75 °C respectively. When looked at in this manner the power consumption does not fall too far short of specifications. Methods of improving this characteristic will be discussed in another section of this report.

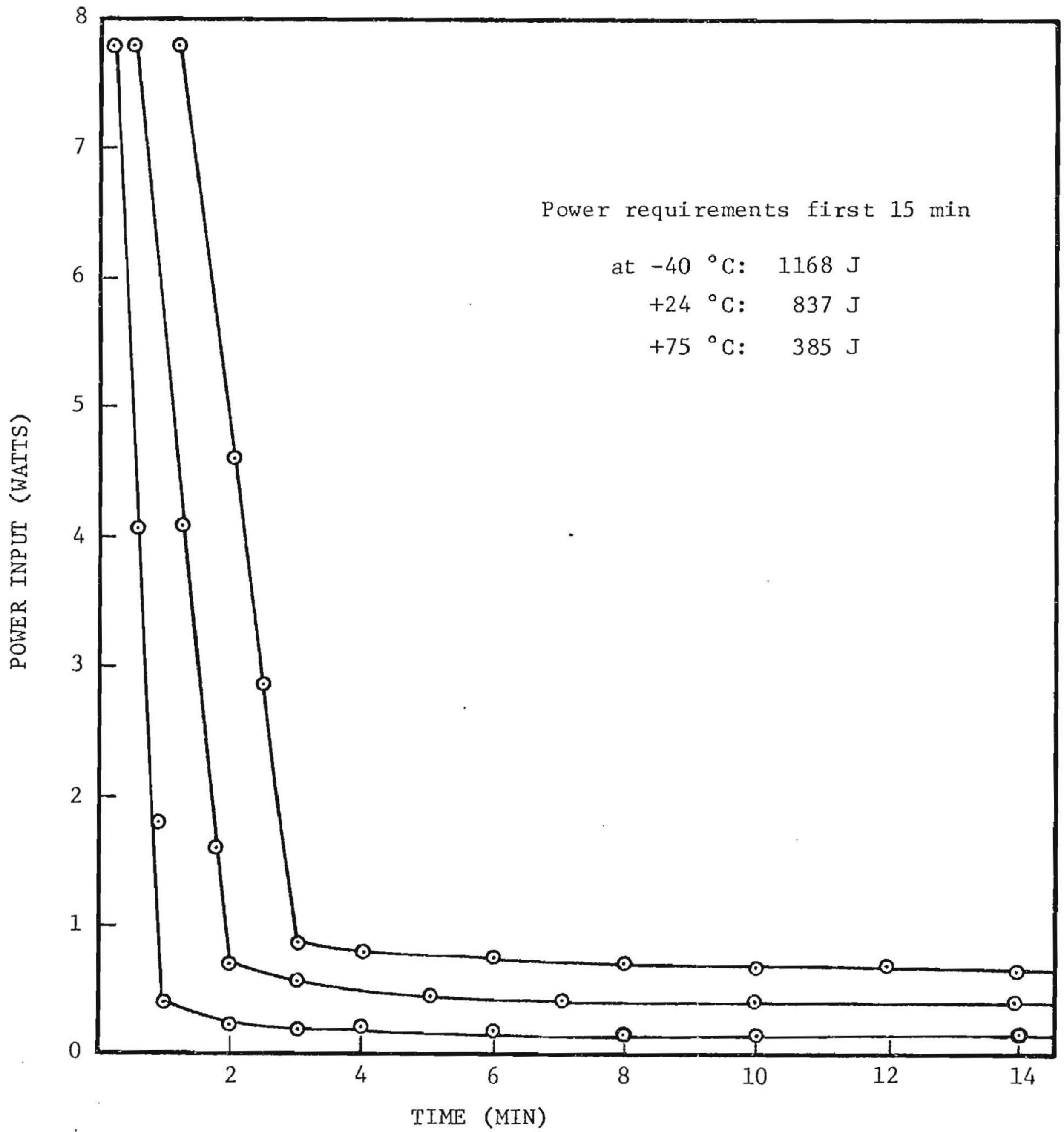

Fig. 3. Warmup power profiles for first 15 minutes after turn-on. The technical guidelines requirement is 810 W-sec over the entire ambient temperature range.

3. Operating Power

The operating power levels for TMXO Model No. 1 in ambient temperatures of -40 °C, +24 °C, and +75 °C, are shown in Fig. 4, as 625 mW, 316 mW, 115 mW, respectively. Figure 4 also shows the total power input to the TMXO for 16 minutes, for each of the three test temperatures. The 250 mW specification is met when the TMXO is operating at approximately 50 °C.

4. Power Aging

This feature was not measured during this evaluation study for two reasons. Firstly, the model under test was not completed in time to conduct an evaluation of its power aging requirement over a one-month period. Secondly, the tests for this report were conducted with the TMXO being continuously pumped and not sealed off.

D. Output Frequency

1. Frequency Adjustment

A fine frequency adjustment of the TMXO was accomplished by means of a miniature 50 KΩ, 25 turn, Bournes type 3280L potentiometer. The adjusting screw was accessible through a hole in the base of the outside can. This potentiometer adjusts the bias on a varicap in the frequency-determining network. The measured adjustment range is $\pm 1.5 \times 10^{-7}$. The 25 turn potentiometer gives a resolution of 6×10^{-9} per turn and is adjustable to $\pm 1 \times 10^{-10}$, of the final frequency.

2. Frequency/Temperature Stability

These data were obtained by firstly operating the TMXO at -40 °C for one hour and then recording its frequency, and then operating it in an ambient of +75 °C for one hour before remeasuring the frequency.

Frequency @ -40 °C = 5,000,000.323.

Frequency @ +75 °C = 5,000,004.016.

From these values a frequency deviation A$\Delta F/F$, of 7.4×10^{-7}, is obtained. As the specification is $\pm 1 \times 10^{-8}$ over the temperature range cited, this requirement was not achieved with Model No. 1.

3. Frequency/Load Stability

This characteristic was determined with an output load resistance (R_L) of 1000 Ω. When the load impedance (Z_L) was 900 Ω - j340 Ω the frequency was $+ 6 \times 10^{-10}$ relative to the frequency at R_L = 1000 Ω. At a load impedance Z_L = 900 Ω + j340 Ω the frequency was -1.6×10^{-9}. The peak-to-peak deviation was 2.2×10^{-9} which is 2×10^{-10} greater than the specification requirement. The peak-to-peak frequency deviation for a resistive load change from 900 Ω to 1000 Ω was $+ 1 \times 10^{-9}$.

4. Frequency/Voltage Stability

The recorded frequency change for an input voltage variation

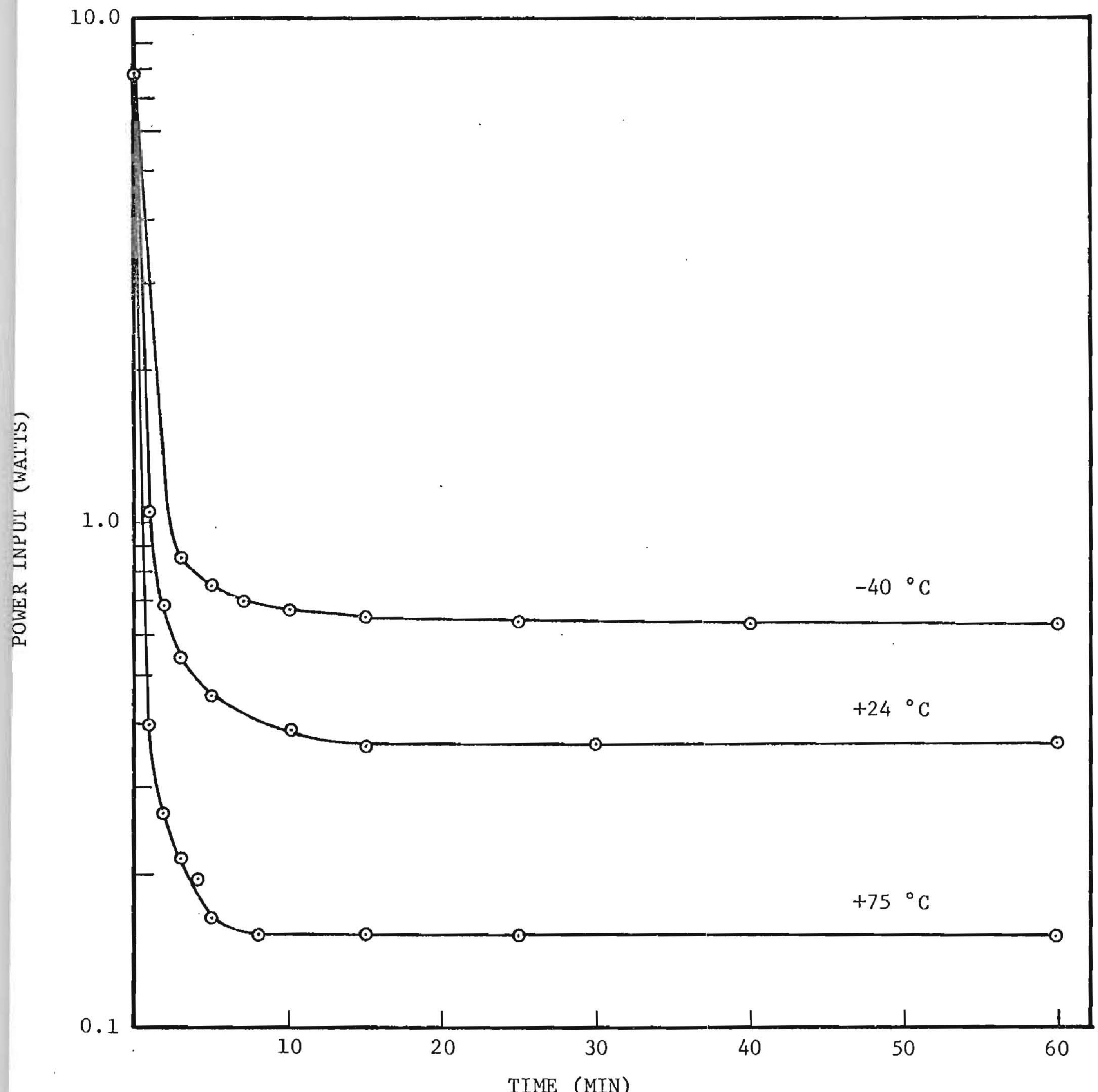

Fig. 4. Total operating power vs time for operating TMXO Model No. 1 in different ambient temperatures.

from 11.4 to 12.6 V dc (12 V ± 5%) was - 1.4 X 10^{9}. This measured frequency change exceeds the specifications (± 1 X 10^{-9}) by 6 X 10^{-10}.

5. Frequency Aging

The aging requirement of ± 2 X 10^{-10}/week after a 30 day stabilization period cannot be met at this time with aluminum plated crystals. However, aging rates as low as a few parts in 10^{10}/hr were obtained after about 24 hours of operation for some of the crystals. These crystals were purchased from Bulova Watch Company.

6. Short Term Stability

Preliminary testing of the (breadboard) prototype oscillator and crystal combination in a separate temperature controlled oven indicated that the short term stability of the oscillator (without the tuning diode network) and crystal should be in the 10^{-11} range for 1 to 10 sec sampling times. The measured short term stability for TMXO Model No. 1 is 4 X 10^{-10} for 10 sec sampling times. Short term stability tests over periods of time from 1 sec to 20 min were not undertaken with this unit for lack of time. Also, it did not appear pertinent to carry out these additional tests when it was obvious from the 10 sec test that this specification would not be met.

E. Warmup Time

Before the frequency vs warmup data were recorded at each ambient temperature the TMXO was allowed to equilibrate in the -40 °C ambient for 45 min and in the +75 °C ambient for 30 min before power was applied to the unit. The pressure readings inside the container, as measured by the ion pump current, during the tests at ambients of -40 °C, 24 °C and 75 °C were 5 X 10^{-7} torr, 4 X 10^{-6} torr and 2 X 10^{-5} torr. The measured warmup data for each of the 3 ambient temperatures are shown in Fig. 5. Also shown in this figure for comparison purposes is the curve representing the required frequency behavior during warmup. On comparing these data it is obvious that the required warmup time vs frequency characteristics were not achieved with this first model of the TMXO.

F. Frequency Recovery at -40 °C Ambient

The output frequency of TMXO Model No. 1 after warmup during each turn-on period was determined for three cycle frequency recovery test and not over a five cycle test as specified. The reduction in number of testing cycles was necessary because of the time element involved. Each cycle consisted of operating the unit for 60 min, then recording the frequency, and then letting the unit sit at -40 °C ambient for a further 60 min period with the power turned off. The recorded frequencies for the three cycles are shown in Table I.

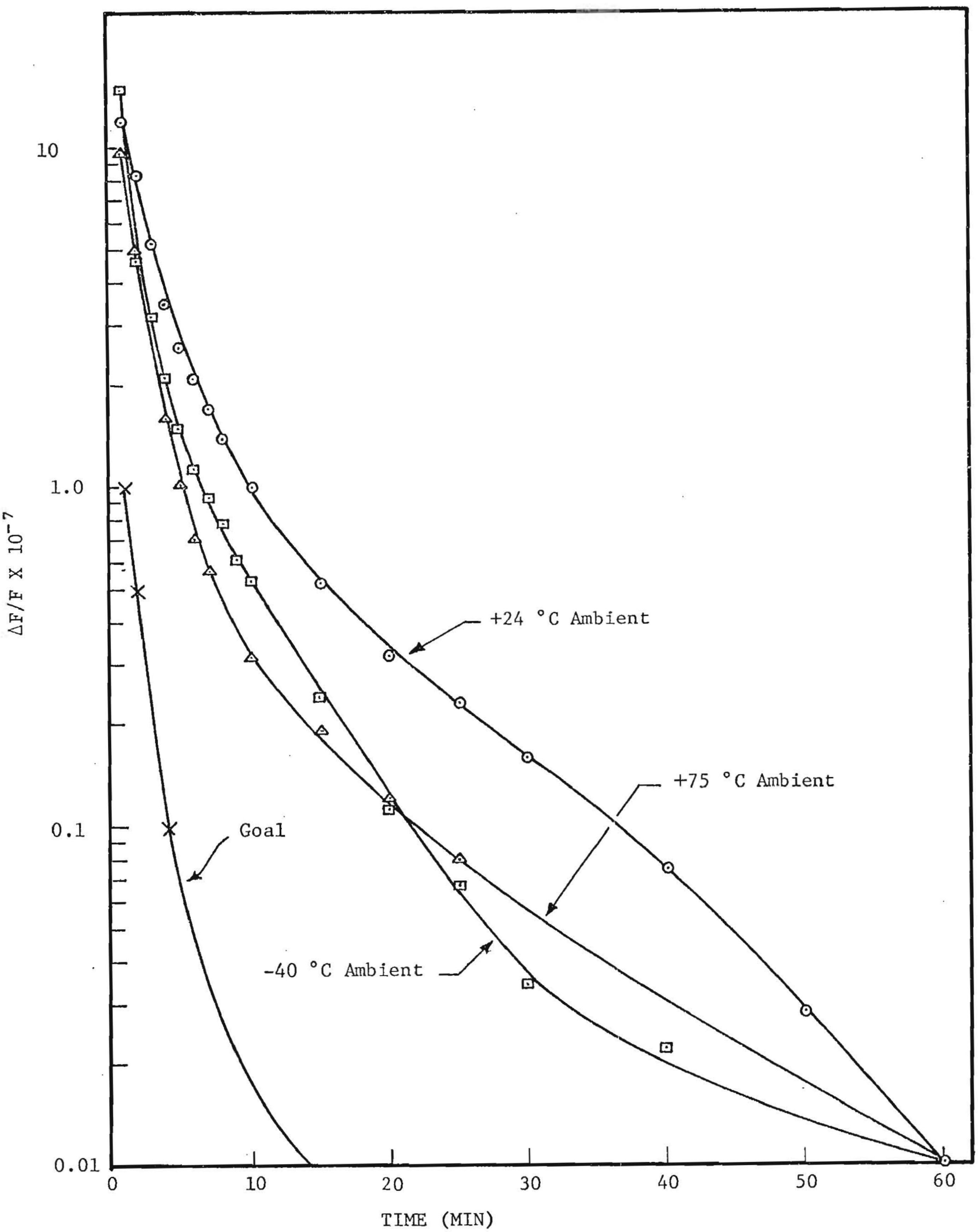

Fig. 5. Warmup time vs frequency for ambient temperatures of -40 °C, 24 °C and 75 °C.

Table I

Frequency of TMXO Model No. 1 During Frequency Recovery Tests of -40°C Ambient

Run Number	Frequency
1	5,000,000.300
2	5,000,000.339
3	5,000,000.302

The maximum frequency deviation was 7.8×10^{-9}.

G. Output Voltage

The nominal output voltage was measured at 177 mV rms across a 1000 Ω load. This measurement was made with a type 545 Tektronix oscilloscope and a 10X probe. This oscilloscope contains an internal calibrater which was used to calibrate the incoming voltage signals.

H. Shock

Since TMXO Model No. 1 was tested while still attached to the small vac-ion 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 of this unit as well as the assembled unit, excluding the outside can and thermal insulation, 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.

IV. SUMMARY OF PERFORMANCE DATA

The performance data for TMXO Model No. 1 and the specification performance data are listed in Table II.

Table II

Measured Variable	Technical Guidelines	Evaluation Data	Deviation from Specifications
Volume	5 cubic in	4.8 cubic in	-0.2 cubic in*
Input Voltage	12 V ± 5%	12 V ± 5%	-
Warmup Power	10 W	7.8 W	-0.2 W
Operating Power	250 mW	625 mW @ -40°C 360 mW @ +24°C 150 mW @ +75°C	+375 mW +110 mW -100 mW
Power Aging	< 1%/month	-	-
Ambient Temp Range	-40°C to +75°C	-40°C to +75°C	-
Frequency Adjustment	5 MHz ± $1X10^{-10}$	5 MHz ± $1X10^{-10}$	-
Adjustment Range	± $1X10^{-8}$	± $1.5X10^{-7}$	-
Frequency/Temp. Stability	± $1X10^{-8}$ (-40°C to+75°C)	$7.4X10^{-7}$ (-40°C to +75°C)	$7.3X10^{-7}$
Frequency/Load Stability	± $1X10^{-9}$ (1000Ω ± 10%)	$2.2X10^{-9}$ (1000Ω)	$2X10^{-10}$
Frequency/Voltage Stability	± $1X10^{-9}$ (12 V ± 5%)	$-1.4X10^{-9}$ (12 V ± 5%)	$+6X10^{-10}$
Frequency Aging	± $2X10^{-10}$/week	-	-
Short Term Stability	± $1X10^{-11}$ (1 sec to 20 min) (± 10 mV and ± 0.2°C)	~ $4X10^{-10}$ (for 10 sec)	-
Warmup Time	± $1X10^{-7}$(1 min) ± $5X10^{-8}$(2 min) ± $1X10^{-8}$(4 min) ± $1X10^{-9}$(15 min)	± $1.5X10^{-6}$(1 min) ± $8.2X10^{-7}$(2 min) ± $3.8X10^{-7}$(4 min) ± $5.3X10^{-8}$(15 min)	$1.4X10^{-6}$ $7.7X10^{-7}$ $3.7X10^{-7}$ $5.2X10^{-8}$
Frequency Recovery @ -40°C Ambient	± $3X10^{-9}$(5 cycles)	$7.8X10^{-9}$(3 cycles)	$4.8X10^{-9}$
Output Voltage	> 0.125 Vrms (1000Ω)	0.177 Vrms (1000Ω)	-

*Minus refers to data which exceeds performance specifications.

V. RECOMMENDATIONS

A. Introduction

According to correspondence with ECOM, dated 8 September 1971, the most important requirements to be met in this contract are 1) volume, 2) operating power, 3) frequency stability and 4) warmup time. In this section we will suggest possible reasons why the prime requirements, listed as 2, 3 and 4 above, were not met in TMXO Model No. 1 and recommend pertinent design changes.

B. Operating Power

The data presented in this report clearly show that Model No. 1 is a long way from meeting the input power specifications.

The major part of this power loss is considered to be down the stainless steel pedestal which supports the crystal unit, oscillator circuit board and temperature control circuit board in the isothermal region of the TMXO. At -40 °C ambient, the heat loss by conduction through this stainless steel pedestal is about 375 mW.

Each of the two subsequent experimental development models will have this support pedestal made of polyimide. The calculated heat loss through this type of support, for a -40 °C ambient, is about 10 mW.

Also, it was necessary to make a last minute change to Model No. 1 by surrounding the electronics in the isothermal region with a 100 mesh stainless steel screen. The purpose of this screen was to reduce the capacitive coupling between the oscillator components and the NRC-2 superinsulation, which is aluminized mylar. This screen was made 7/8" in diameter by 1 1/8" long and supported from the type-D base of the TMXO by four stainless steel wires, each 0.030" in diameter. This screen and support wires represent a thermal drain of about 50 mW at -40 °C ambient.

Sixteen layers of NRC-2 insulation are used between the screen and the outer wall of the unit. This insulation provided good thermal shielding for both top and sides of the core. It was difficult, however, to adequately shield the lower region of the isothermal region from the base and items attached to it, i.e., voltage regulator and trimpot housing. A more suitable NRC-2 insulation technique should be possible with Models Nos. 2 and 3. One of the changes that we propose to make in these models is to secure the stainless steel screen to the polyimide post. This will allow the NRC-2 to be more efficiently wrapped around the pedestal and will also eliminate the 50 mW heat loss down the stainless steel wires.

As an alternate insulation material to NRC-2 we have considered a fume silica powder, manufactured under the trade name of CAB-O-SIL[R]. This material has a reported K value of 2.2 X 10^{-5}W/cm/cm^2-°C, which is two orders of magnitude poorer than NRC-2 but better than most other insulating materials. We tried to obtain some performance figures with CAB-O-SIL insulation in Model No. 1 before NRC-2 was used in the final assembly. A vacuum leak in the outer can prevented us from obtaining any reliable data in the time available to carry out the experiment.

Should NRC-2 superinsulation prove unsatisfactory for the TMXO application, then a serious investigation of CAB-O-SIL as an alternate insulation should be conducted.

The voltage regulator (Fairchild type μA723) that has been used in this TMXO is also a source of power loss as it dissipates about 20 mW. At this time it appears that it may be possible to replace the voltage regulator with several low level zener diodes. As these diodes have a very low heat dissipation it would be possible to locate them on the oscillator chip in the isothermal region.

Thus, simple changes in the pedestal, screen supports and voltage regulator should reduce the power consumption under the most unfavorable operating conditions by some 435 mW. An improved method of applying NRC-2 superinsulation should further decrease thermal losses to a level which will allow the TMXO to operate within the operating power specifications.

C. Frequency Stability

1. Short Term Stability

We are unable to meet the requirement of $\pm 1 \times 10^{-11}$ with Model No. 1. The exact reason is unknown but we suspect the small temperature fluctuations due to improper gain setting of the OP amps in the temperature control circuit. However, measurements made before closing the package gave acceptable short term stability. The frequency/temperature sensitivity of the MOSFET oscillator is low. The crystal would, however, show the order of short term fluctuations obtained with temperature variation of less than 0.01 °C. In Models Nos. 2 and 3 special attention will be given to achieving the optimum gain of the temperature control circuit. The reduction of the heat leakage paths described in the previous section should also stabilize the temperature and thus the frequency.

2. Frequency/Temperature Stability

The desired frequency/temperature stability was $\pm 1 \times 10^{-8}$ measured at -40 and 75 °C. We obtained 7.4×10^{-7}. We suspect this performance is due to the positive temperature coefficient of voltage on the voltage regulator attached to the base of the assembly where it is exposed to the full ambient temperature range. The regulator output voltage (9 V) is further stabilized by a zener diode on the oscillator board before being used to supply bias to the frequency trimming varicap. Calculations based on "book values" of performance data of the various components indicated this arrangement to be suitable. The actual operation of individual components can of course vary from the published parameters. Very small changes in voltage applied to the frequency trimming varicap may be the source of the frequency deviation with ambient temperature. As a solution we have thermally isolated the voltage regulators in Models Nos. 2 and 3, mounted in type TO-5 cans, by using 1/4 inch polyimide spacers between regulators and bases. The regulator cannot be in the isothermal region because it dissipates ~ 20 mW of electrical power, far too much when the ambient approaches 75 °C. The regulator, insulated from both the base and isothermal region, will operate at a temperature determined mainly by its own dissipation rather than by the ambient and thus should deliver output voltage that is relatively independent of ambient temperature.

D. Warmup Time

There are two factors to consider under this heading: 1) the power consumed and 2) the rate at which the frequency reaches the final stability. We are allowed 600 W-sec after turn-on. In the worst case (-40 °C, ambient) we are using 546 W-sec for warmup, although the operating power does not drop immediately to the "steady" value. Improved insulation and mounting methods will reduce the power requirements during warmup. We feel, however, that we have already exceeded this requirement.

The frequency warmup requirements were not met. We are almost certain that some of the problem is the retrace effect of the Al plated resonators. Some years ago we found* that Al plated resonators aged more at low temperatures than at high temperature (i.e., 85 °C). This action was conjectured to be due to the enhanced sticking coefficients of ambient atoms and/or molecules at the lower temperature. We also noted that resonators which had been stored at temperatures well below 85 °C for some time aged in a positive direction after returning to 85 °C. The frequency behavior we obtained for the TMXO during the first hour of the warmup strongly suggests that the action described above is occurring. The solution would be to use another metal for the resonator electrodes; this we cannot do under the present contract.

E. Other Recommendations

The operating frequency (5 MHz) at 85 °C of a given crystal is adjusted into the range of the trimming potentiometer by making small corrections in the load capacitance network facing the crystal. After the enclosure is sealed the only means of making additional adjustments, if needed, is with the limited-range trimpot. An external coarse adjustment with a range of $\pm 1 \times 10^{-6}$ is needed. Actually, the most convenient arrangement would be to make the frequency trimming operations external to the TMXO as is done for the one cubic inch version under development by the Bendix Company.

---

*R. B. Belser and W. H. Hicklin, "Quartz Crystal Aging Effects," Technical Report ECOM 0182-2 (May 1968).

AD

RESEARCH AND DEVELOPMENT TECHNICAL REPORT

ECOM-0301-F

TACTICAL MINIATURE CRYSTAL OSCILLATOR

FINAL REPORT

by

R. K. Hart, W. H. Hicklin and L. A. Phillips

April 1973

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TR ECOM-0301-F
April 1973

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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

DISTRIBUTION STATEMENT

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ABSTRACT

The purpose of this work was to develop an experimental tactical miniature crystal oscillator (TMXO) in a 5 in^3 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.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

LIST OF FIGURES

LIST OF FIGURES (CONTINUED)

I. INTRODUCTION

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 enclosre 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.

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* All State Welding Alloy Co., White Plains, N. Y.

**Product of the Cerro Corporation, New York.

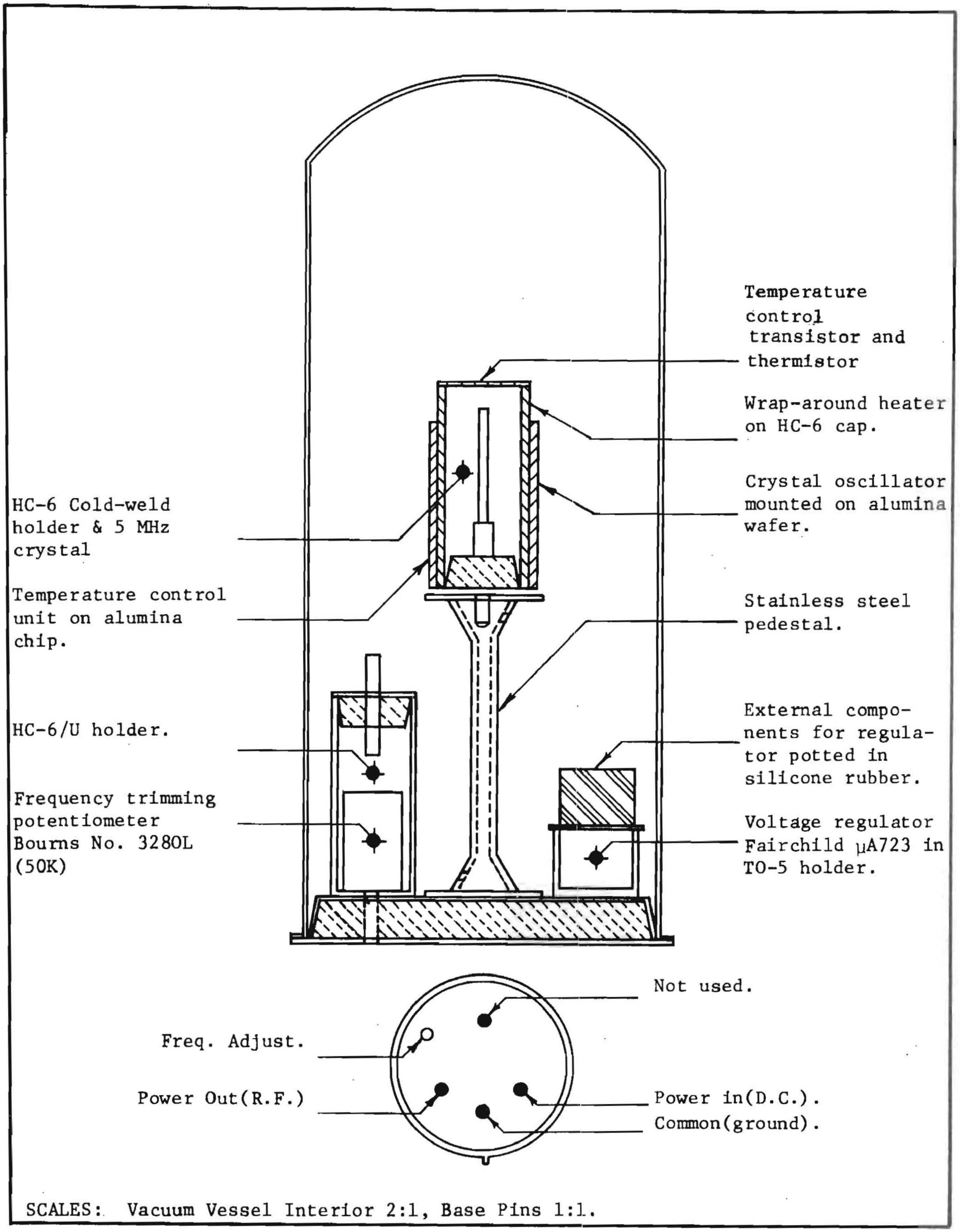

Fig. 1. Basic conceptual design of TMXO.

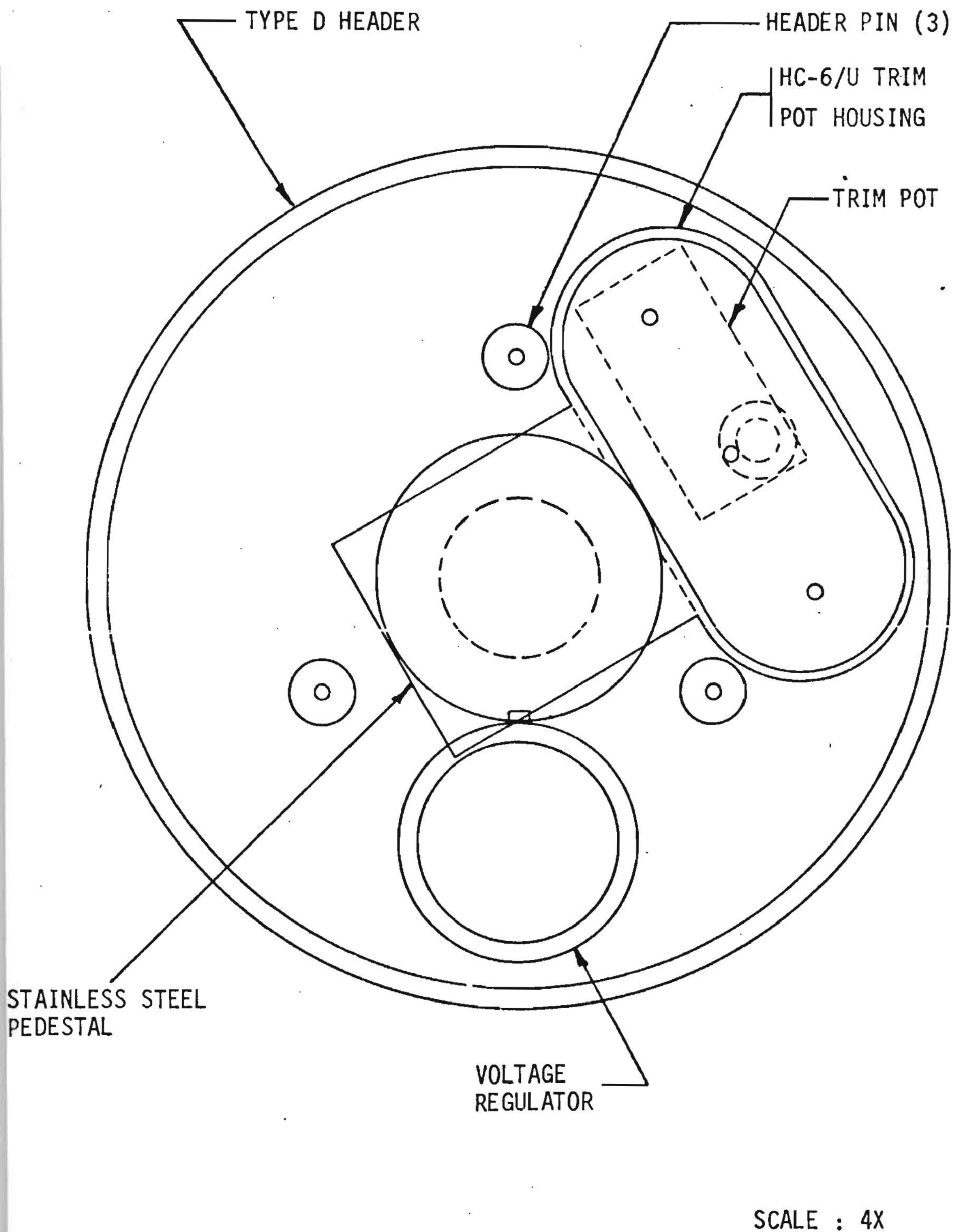

Fig. 2. Layout of components on the type "D" base.

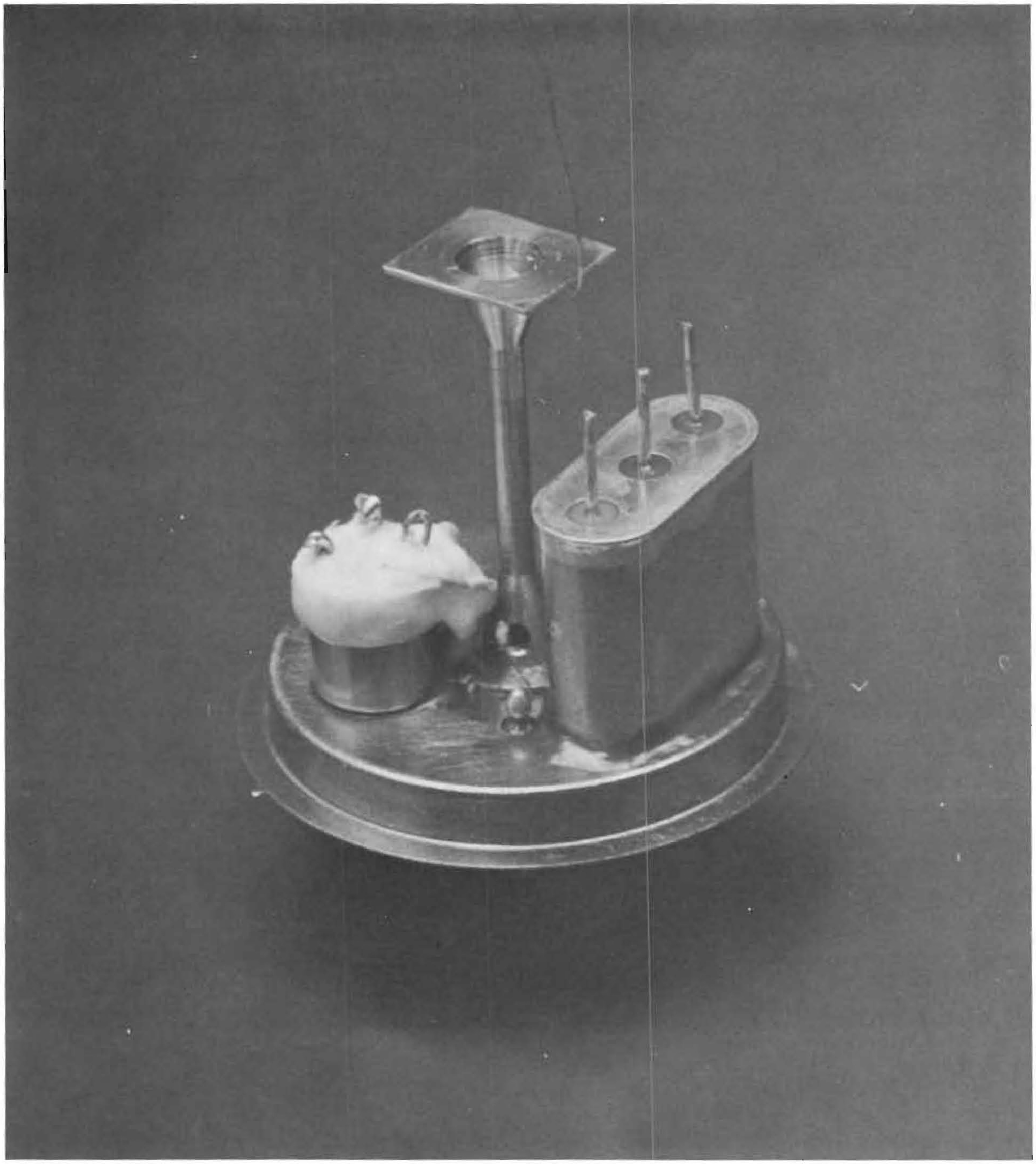

Fig. 3. Photograph of Base Assembly.

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, Q_2, 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

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* 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.

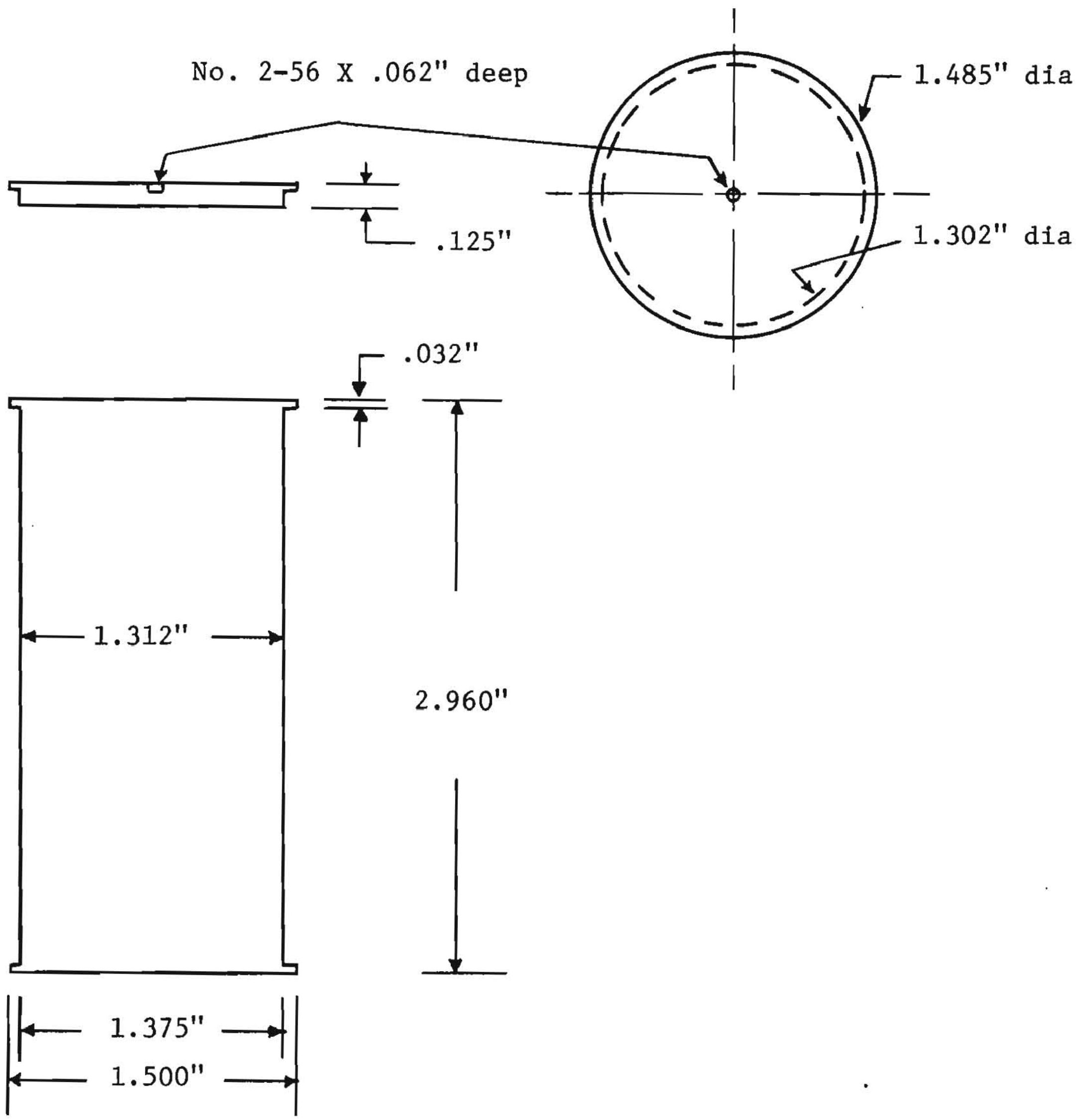
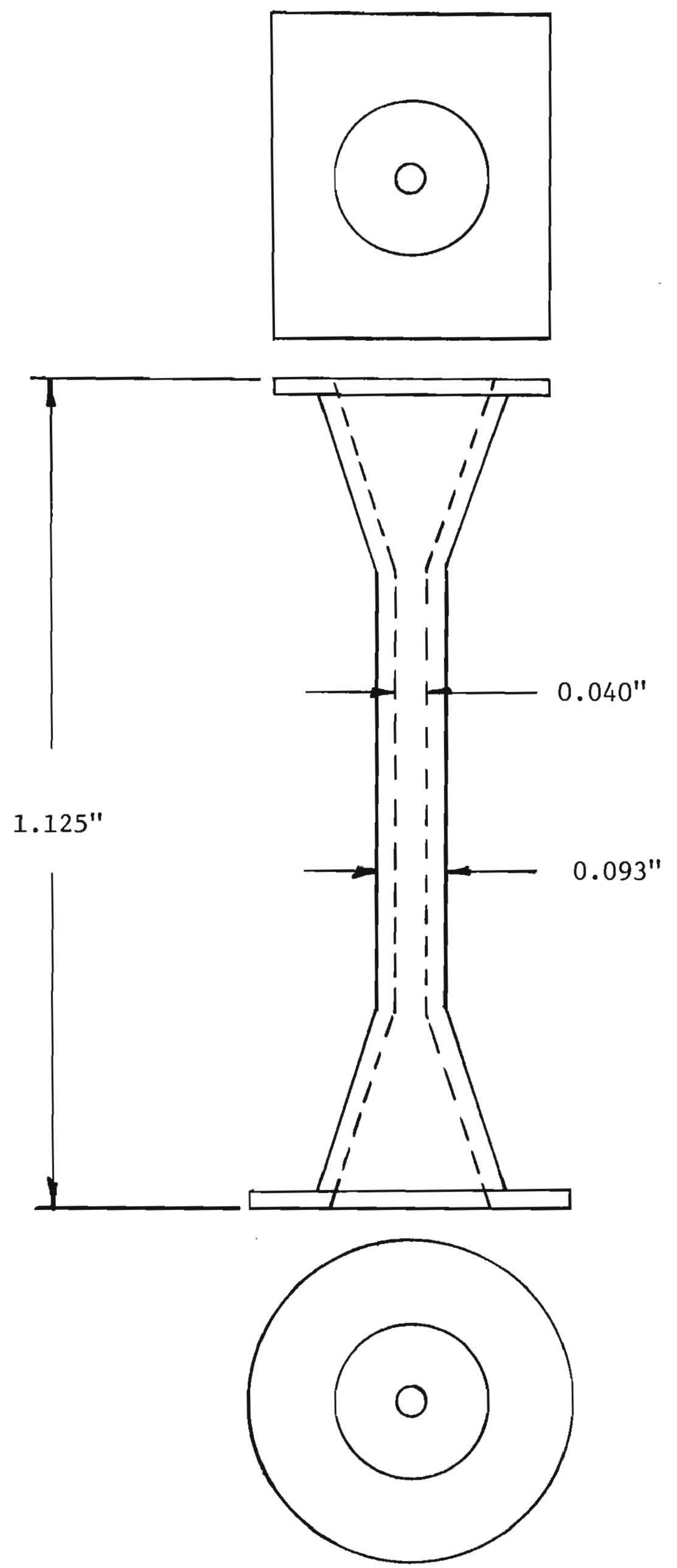


Fig. 5. Two-piece cap for Models Nos. 2 and 3.



MAT'L : 304 SS

SCALE : 4X

Fig. 6. Stainless-steel support pedestal. Lower (round) end spot-welds to Model No. 1 base. Upper (rectangular) end attaches to HC-6 holder.

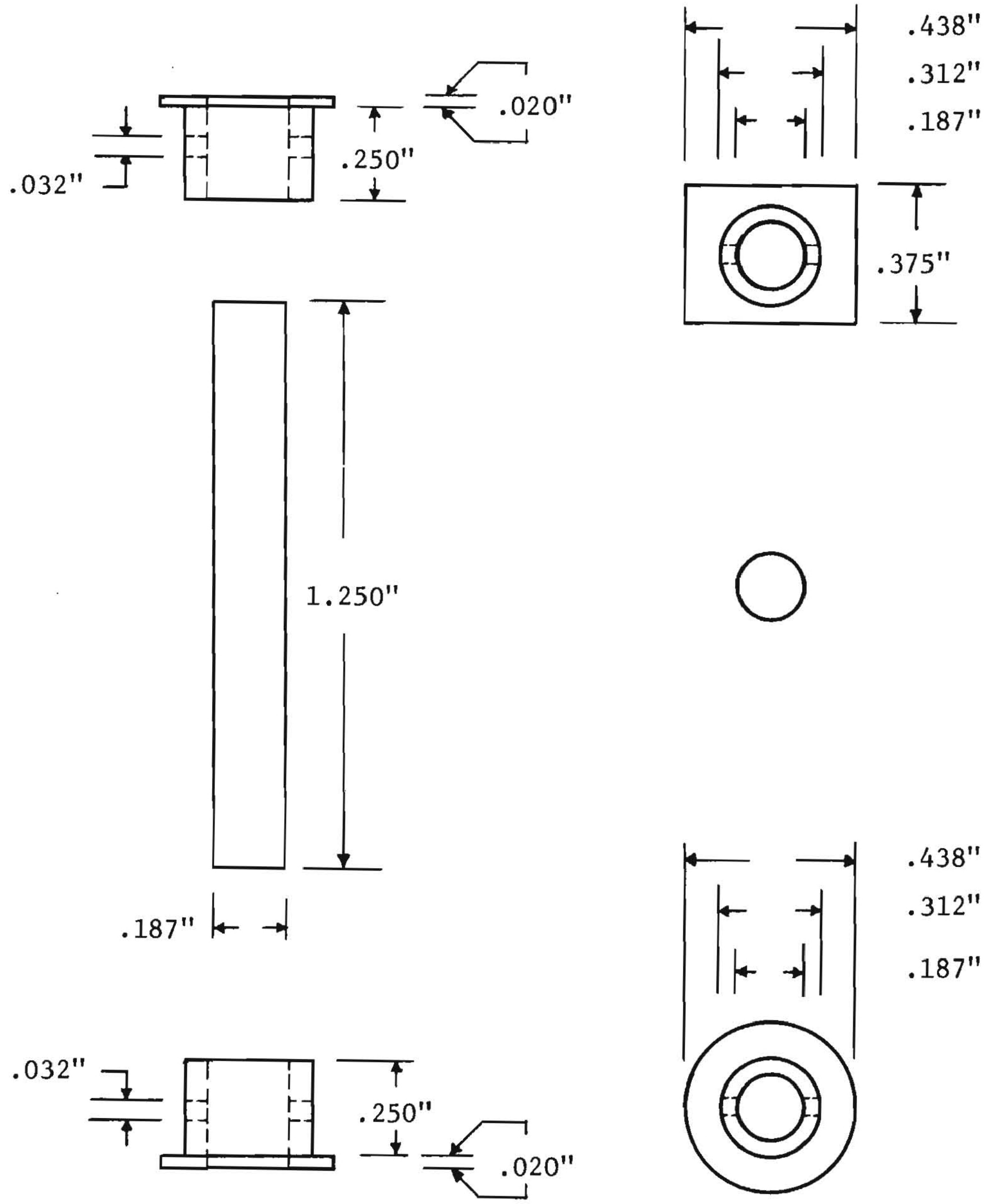


Fig. 7. Support pedestal assembly for TMXO Models Nos. 2 and 3.

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

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* 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 $-40°C$ ($\Delta T = 125°C$) the K value of the thermal insulation must be about 2×10^{-5} W cm/cm^2 ΔT. Few materials approach within even one order of this value. The plastic foam insulators have K values of 2×10^{-4} or more depending 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 4.1×10^{-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 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 insulation 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

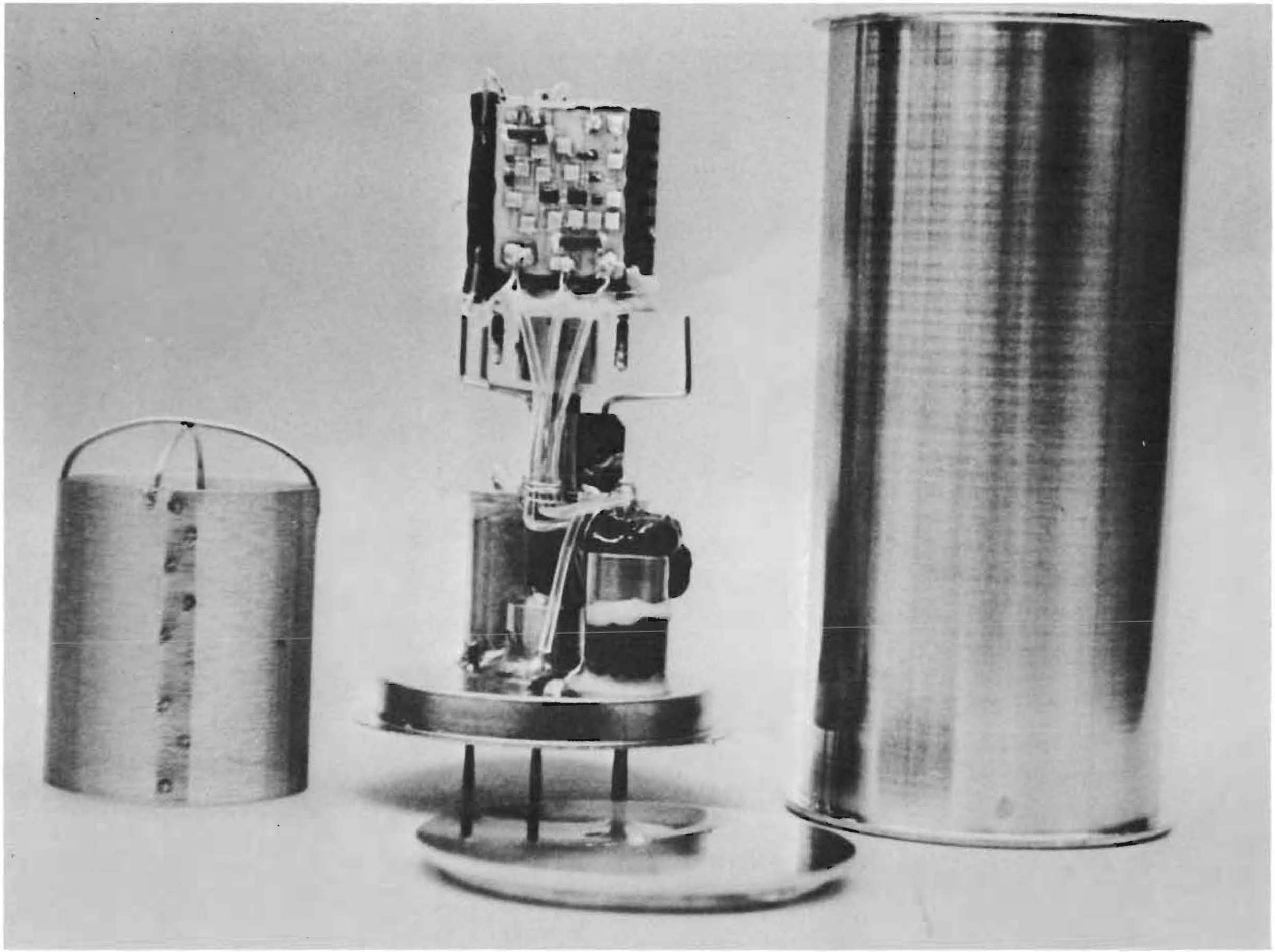


Fig. 8. TMXO No. 3 before NRC-2 and cap installed.

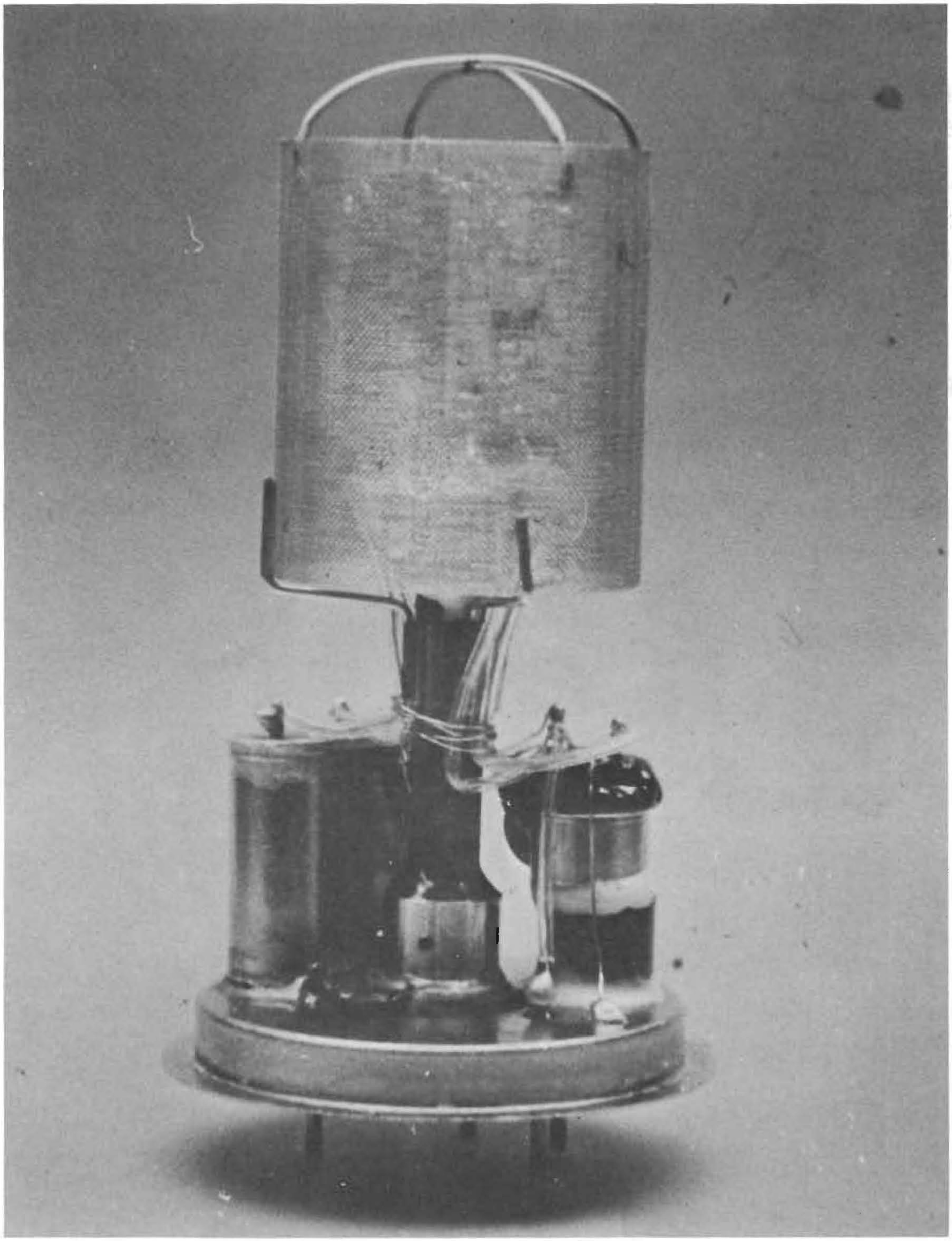


Fig. 9. TMXO No. 3 showing screen installation.

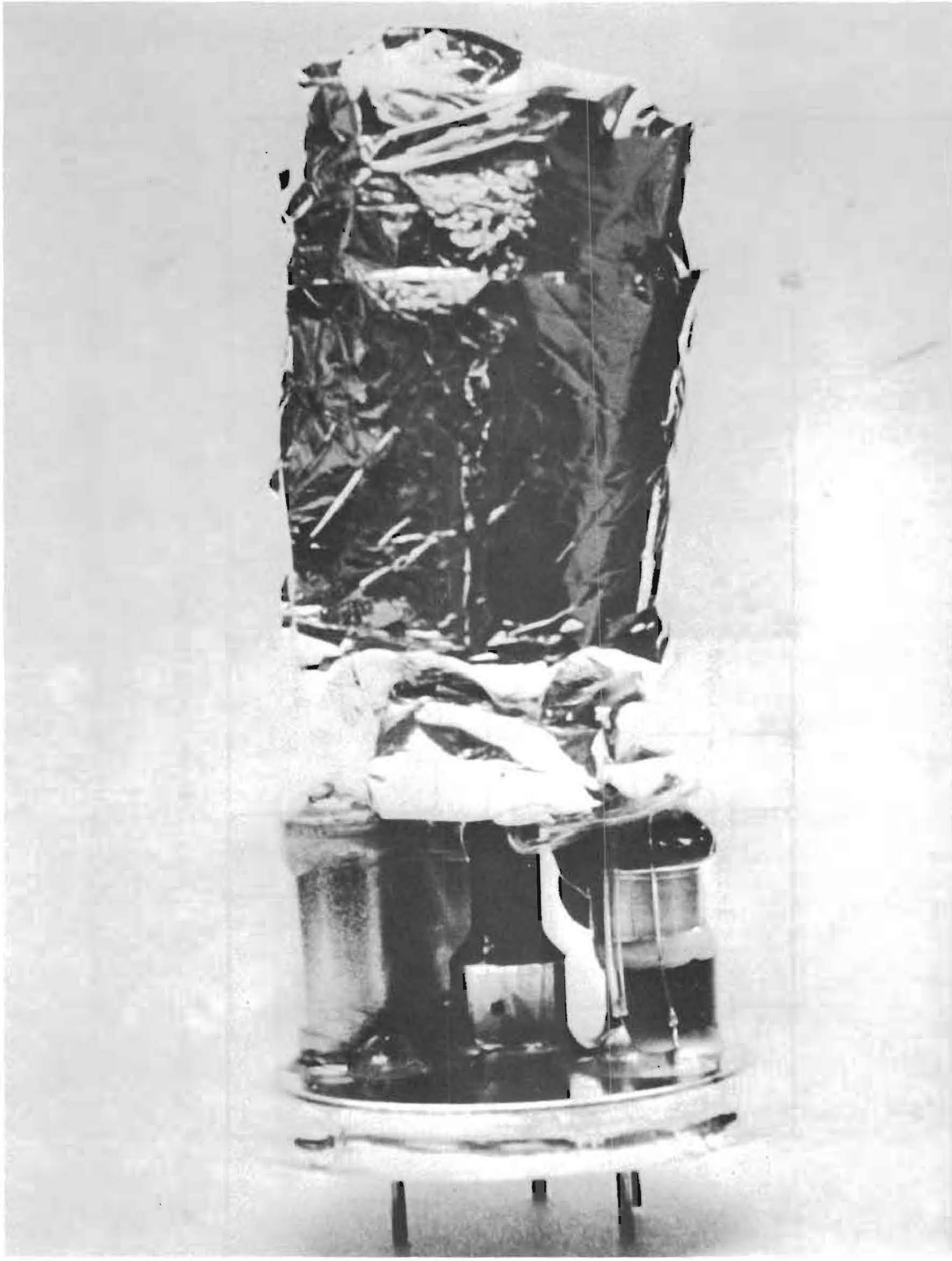
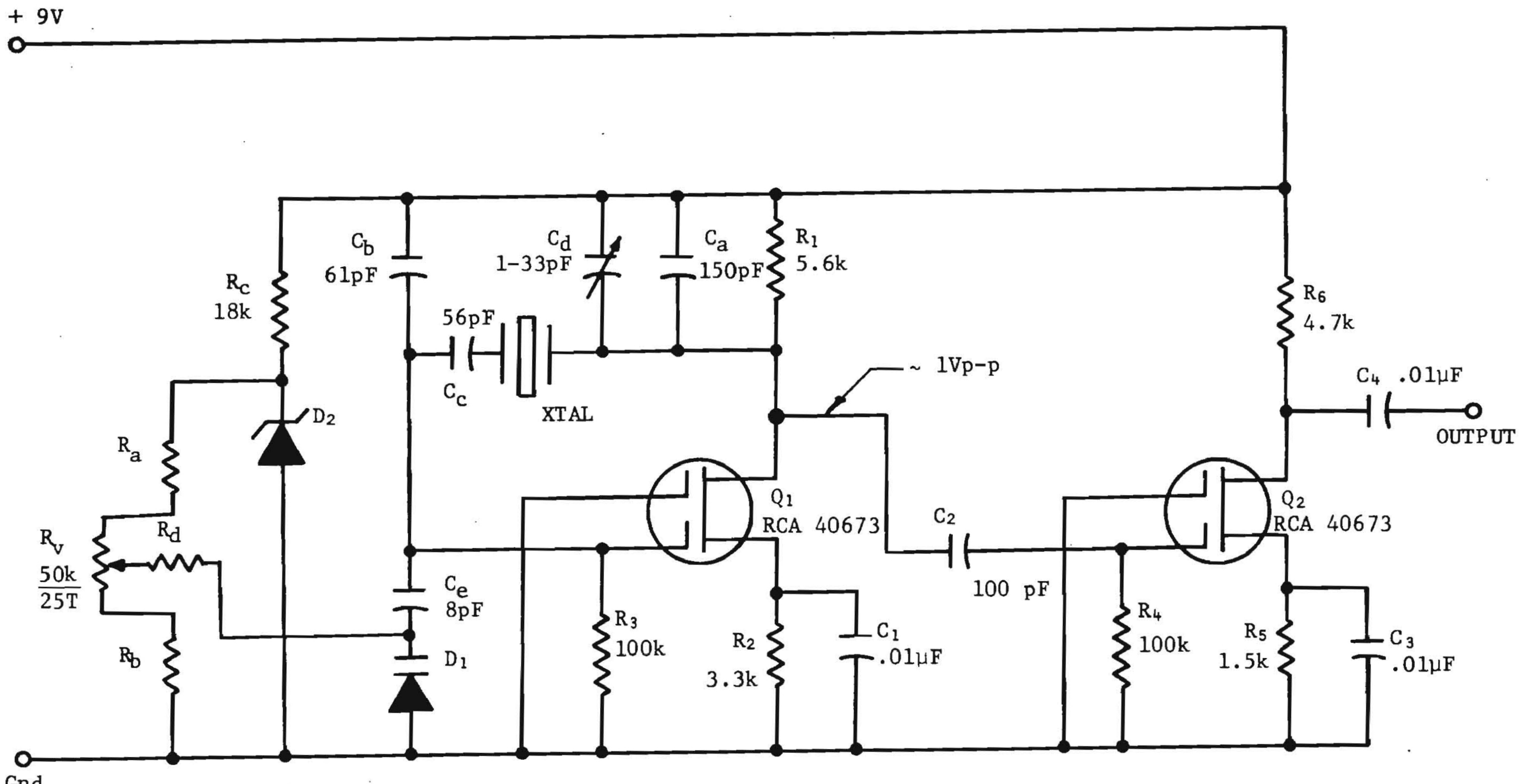


Fig. 10. TMXO No. 3 showing NRC-2 installation.



R_a, R_b, and R_d selected for final frequency adjustment.

Fig. 11. Circuit diagram of the MOSFET Crystal-Controlled Oscillator.

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 2×10^{-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 1×10^{-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 μA 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 ± 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 ΔC_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 ± 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 8×10^{-10} or $1 \times 10^{-10}/45°$ 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,

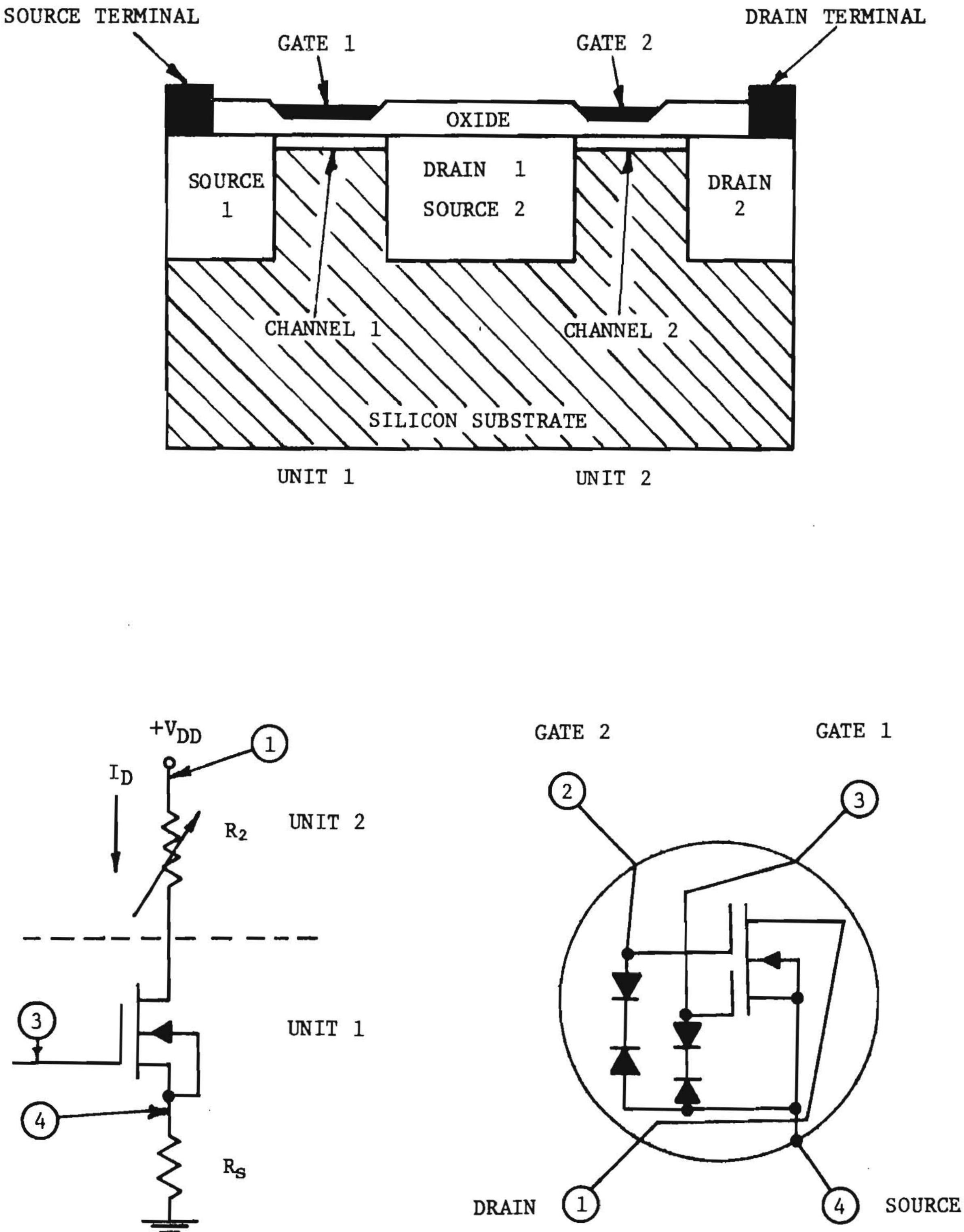


Fig. 12. Equivalent circuit representation of the two units in a dual-gate MOSFET.

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 X 10^{-11}/mV change in input voltage and without input regulator or tuning diode, D_1; (2) Frequency/Load Stability of less than 1 X 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 ± 1 X 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 D_2 (4.5 V) prevents the output of OP-2 from driving Q_1 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 ±4.5 V described above. When the bridge becomes unbalanced, the output from OP-2 increases and D_2 conducts, applying drive to Q_1.

Transistors Q_1 and Q_2 are connected in a Darlington configuration and provide a gain of approximately 30. Transistor Q_2 is mounted on top of the crystal holder as described previously. After the initial warm-up period, Q_2 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 set 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 R_{4a} and R_{4b} (see Fig. 13) sets this temperature. Resistor R_{4b} is a Motorola type MMCR-100-025 or MMCR-100-100. These chip resistors can be varied in 25 Ω or 100 Ω 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.

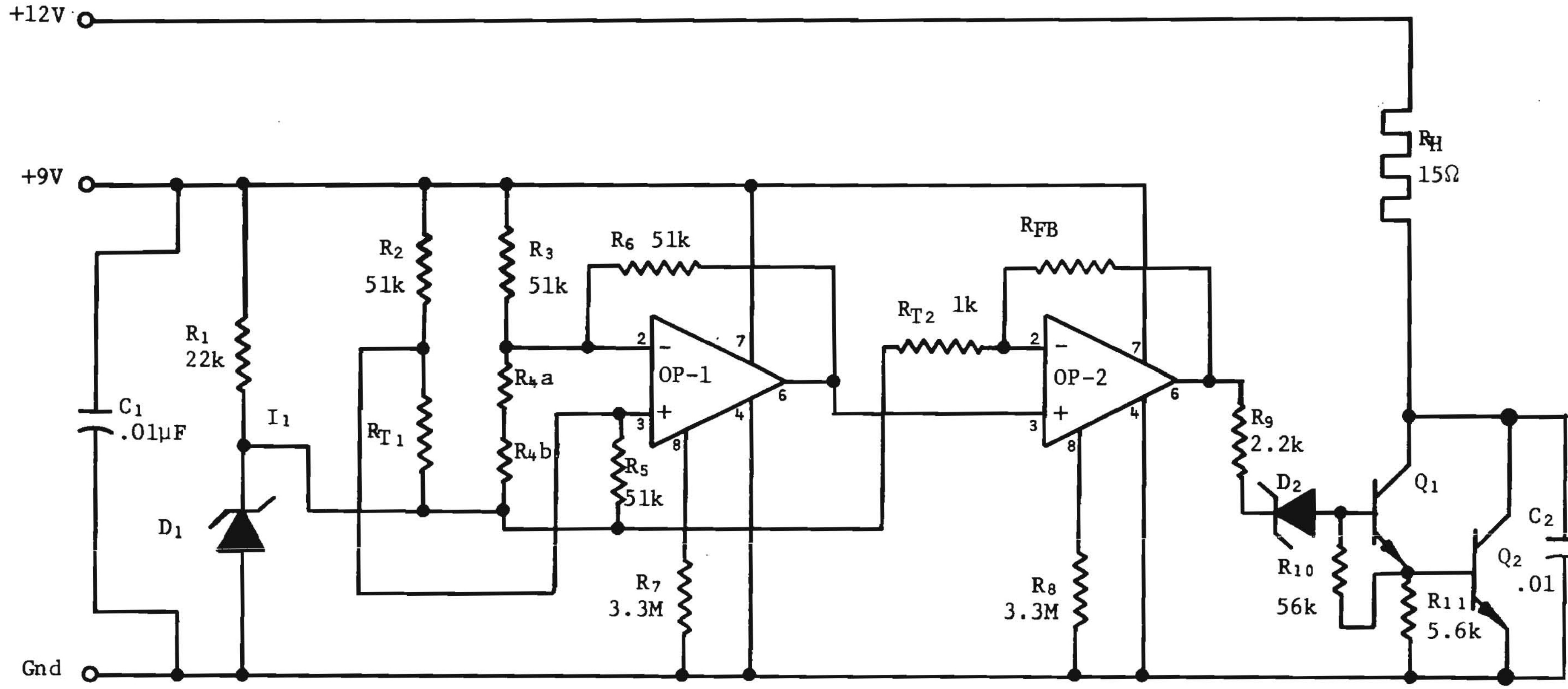
3. Voltage Regulator

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 ± 5% of 0.01% of the output voltage.

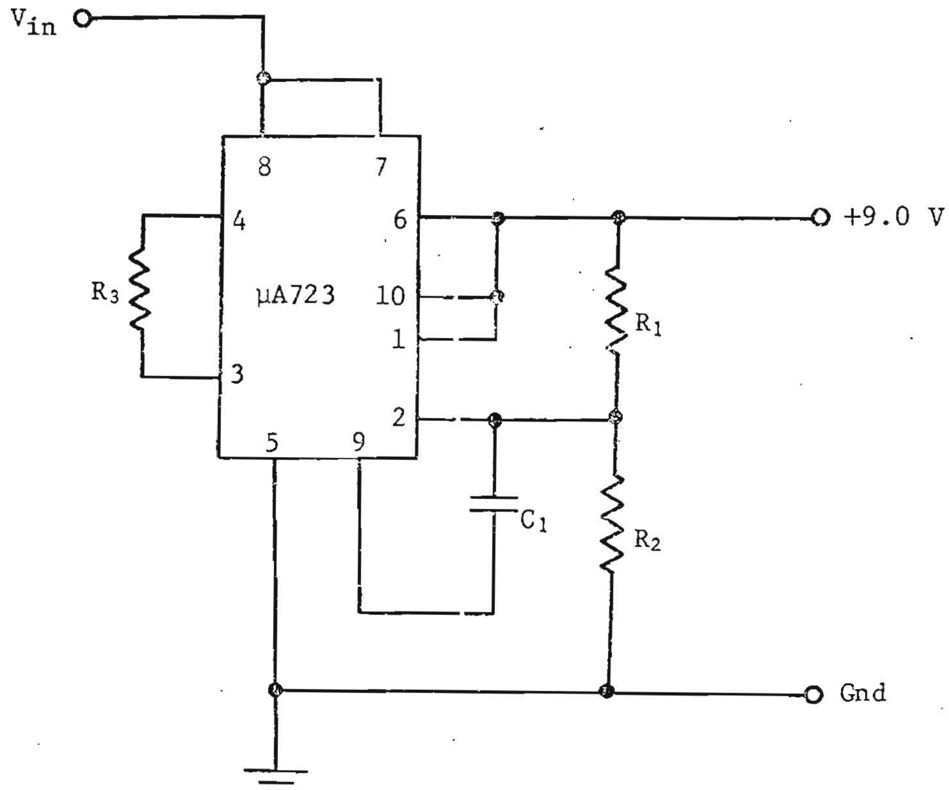
The input power to the regulator is about 30 mW with a 1 mA load current, with the regulator requiring about 20 mW of this power. The 30 mW load is the total power requirement for all electronic circuitry, excluding the crystal heater.

In constructing the complete voltage regulation unit all the external components were soldered directly to the Fairchild type μA723 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.



OP-1, OP-2 : µA776
D_1, D_2 : MZC4.7B1 MOTOROLA
R_{T_1} : VECO THINISTOR TYPE FN1A6
R_4 : TRIM TO SET TEMPERATURE
Q_1 : MOTOROLA UNENCAPSULATED TRANSISTOR MMCS2222
Q_2 : MOTOROLA UNENCAPSULATED TRANSISTOR MJC082

Fig. 13. Schematic diagram of temperature control circuit.



R_1 : 1.5kΩ/1/8 W
R_2 : 6.8kΩ/1/8 W
R_3 : 1.5kΩ/1/8 W
C_1 : 100 pF
V_{in} : 12 V ± 5%

At 12 V input and load current of 1 mA the power input is 30 mW.

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.

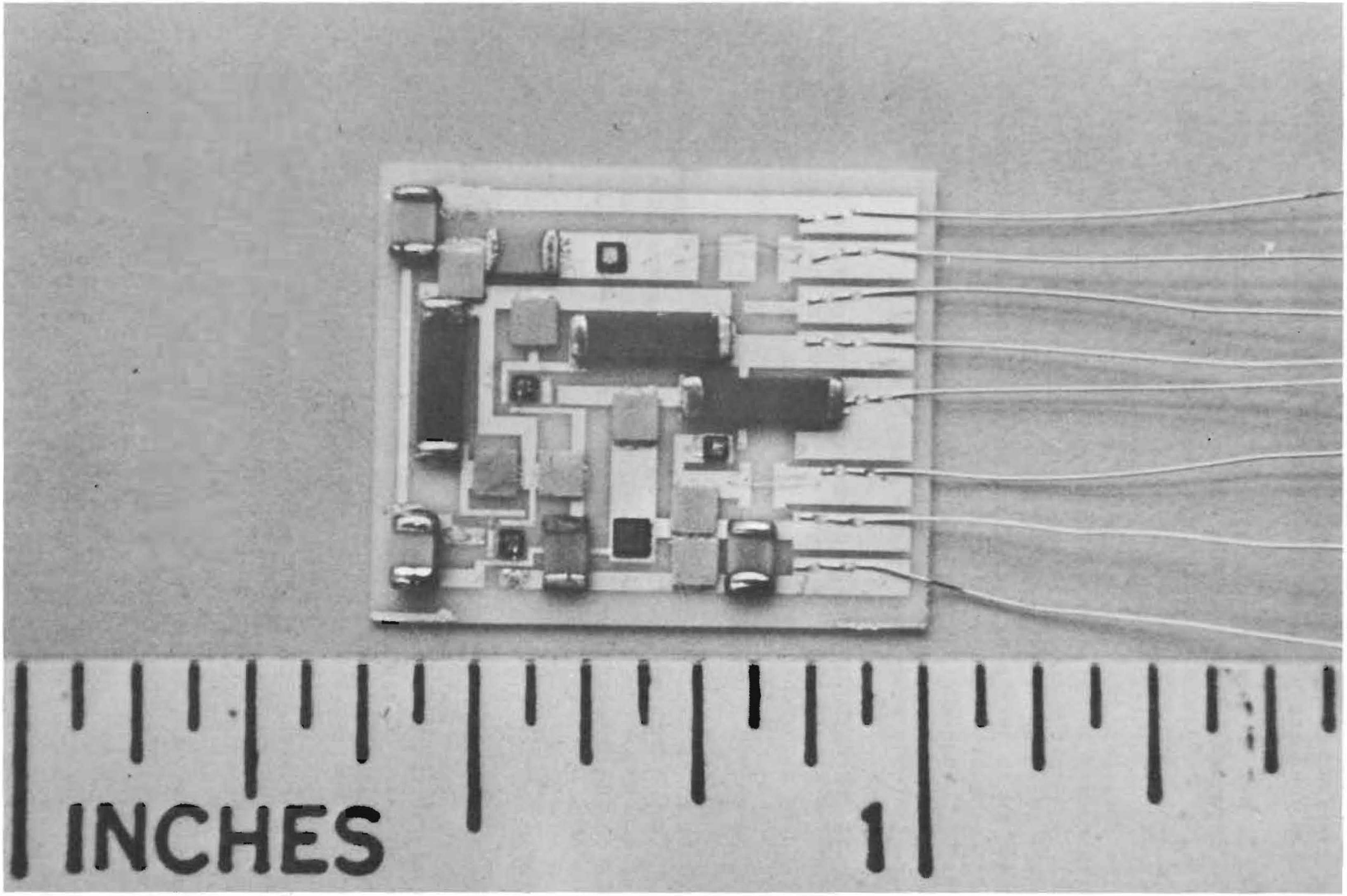


Fig. 15. Photograph of hybrid oscillator board.

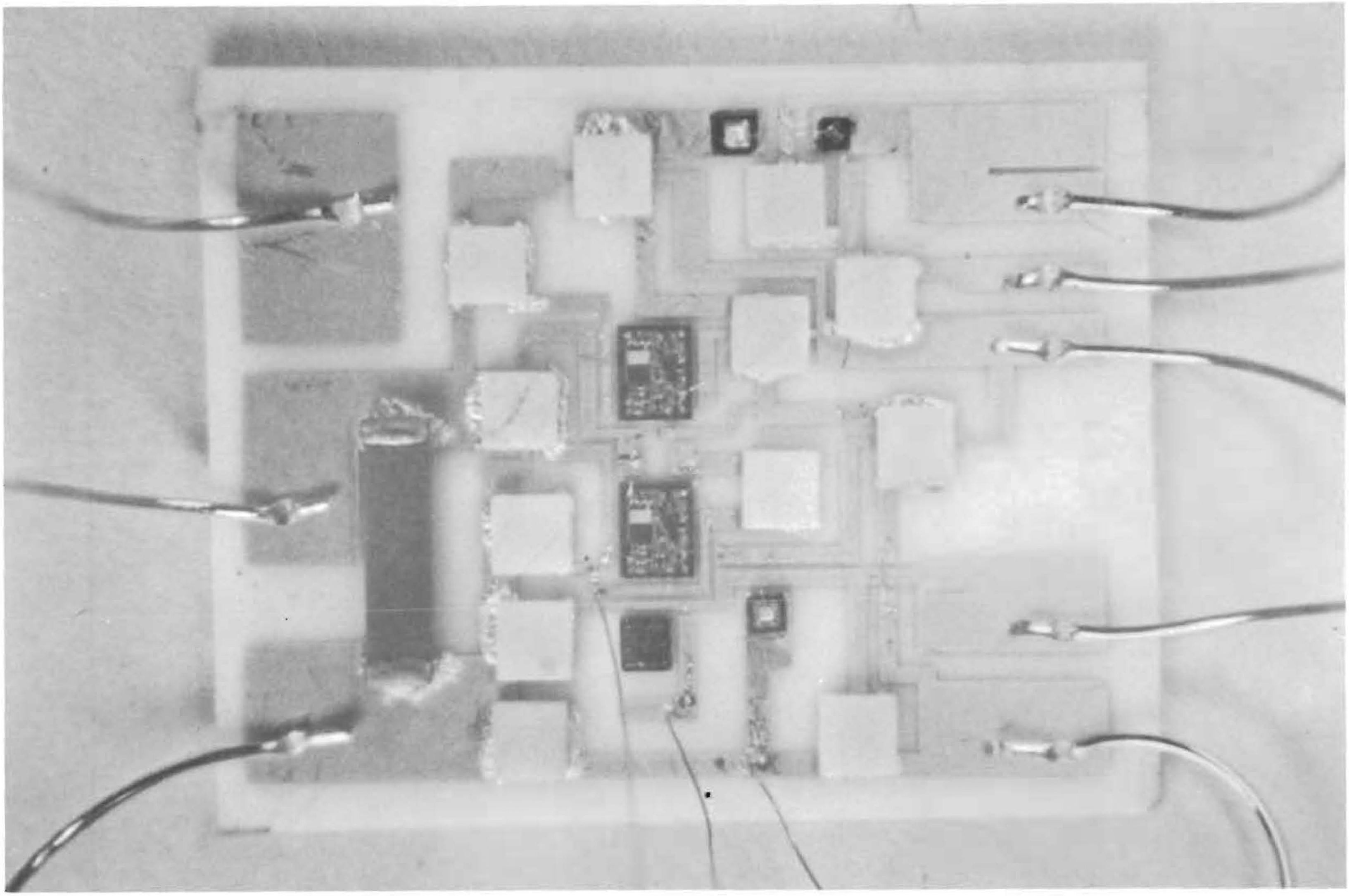


Fig. 16. Photograph of hybrid temperature circuit board.

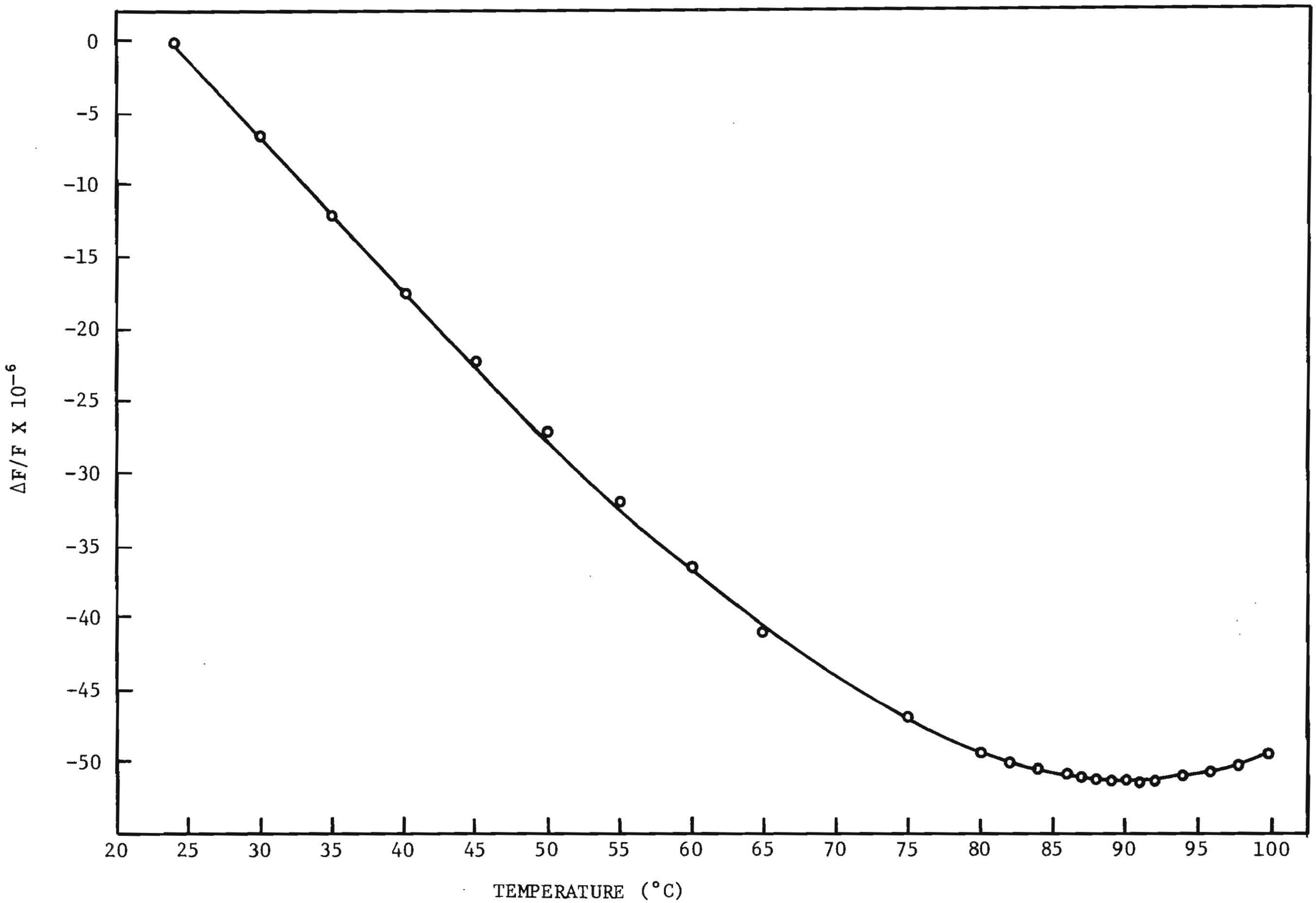


Fig. 17. Temperature coefficient of frequency of unit 6.

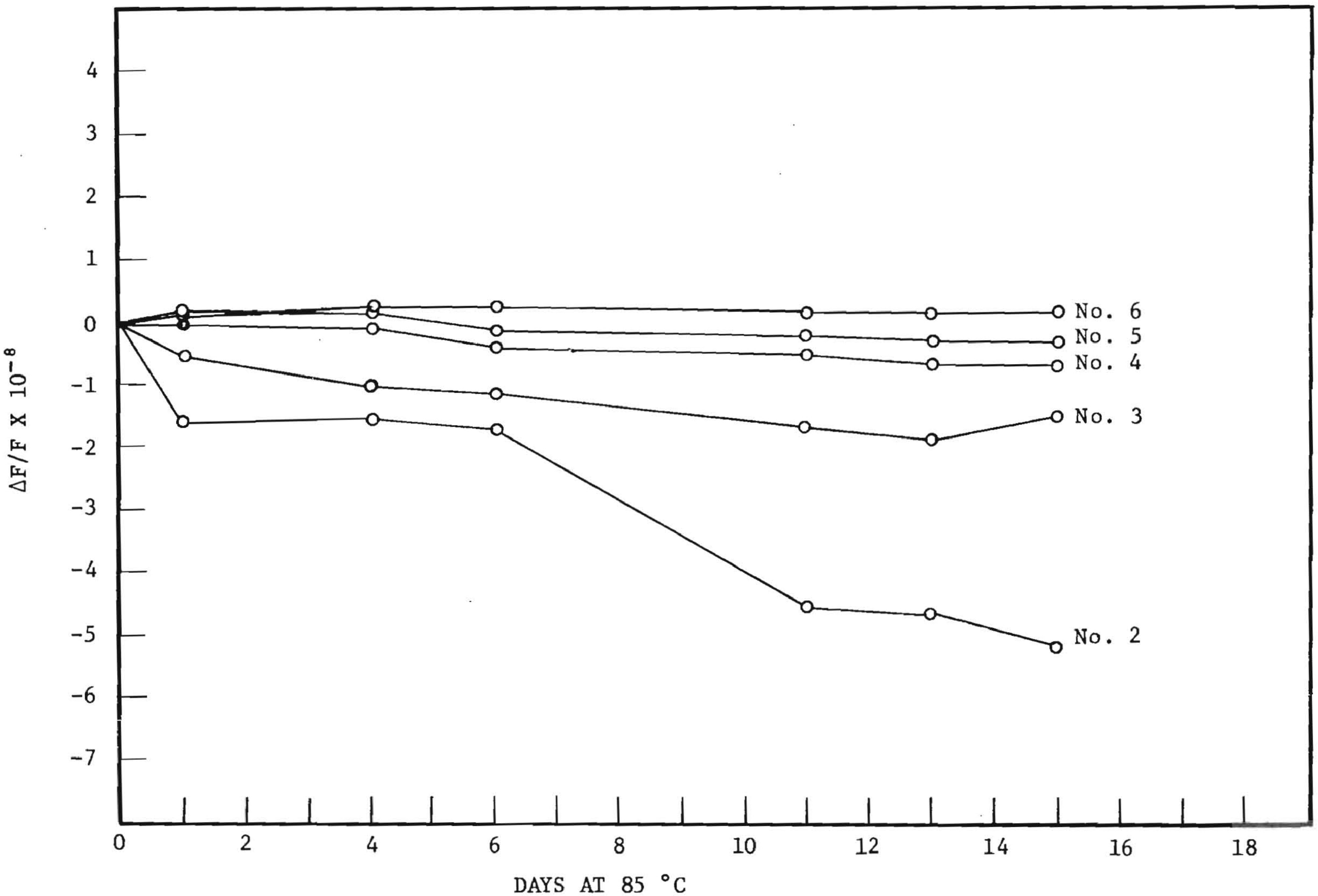


Fig. 18. Aging data for 5 MHz resonators purchased for the tactical miniature crystal oscillator.

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 $\pm$ 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.

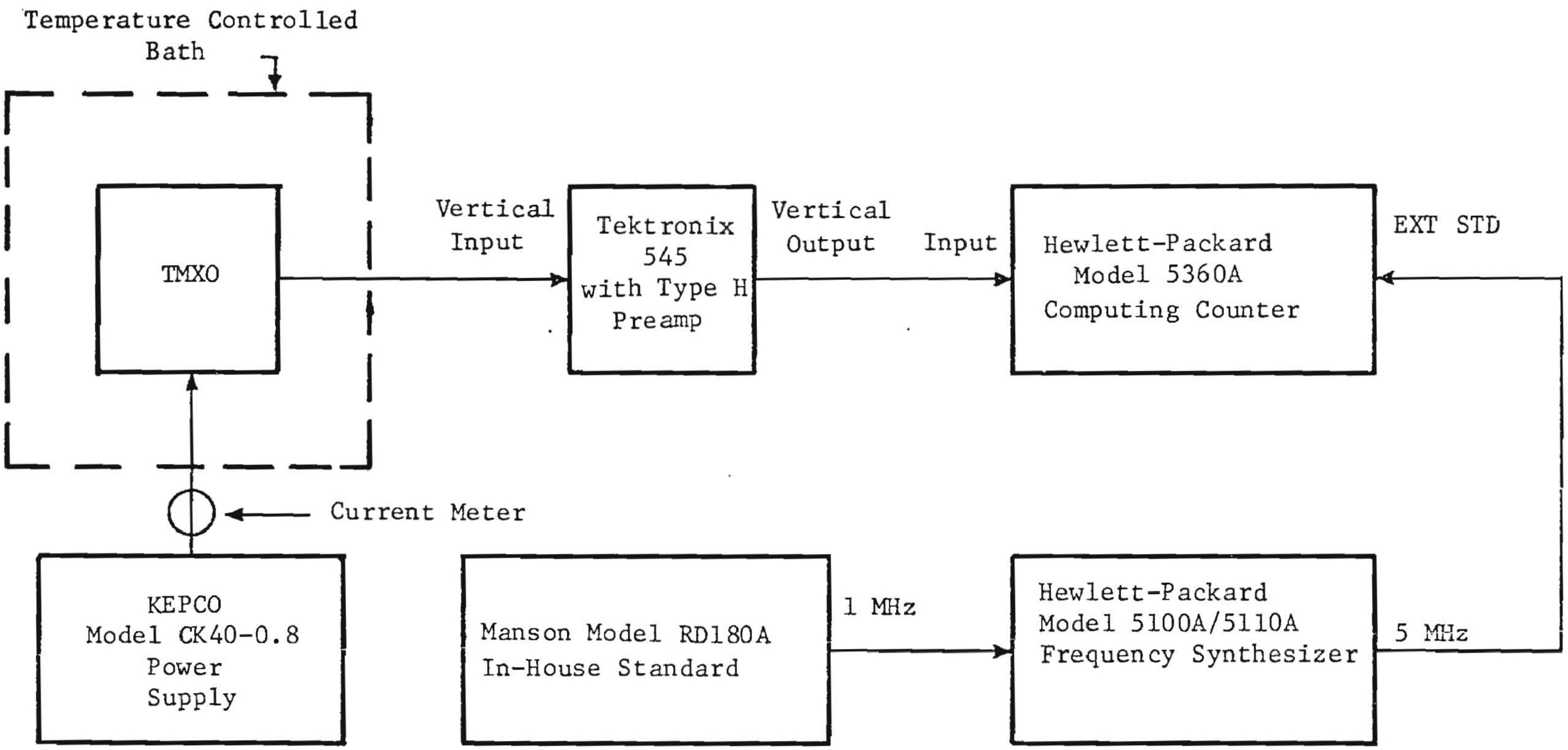


Fig.19. System for the measurement of warmup time, warmup power and the frequency during and after warmup. Frequency readout is digital.

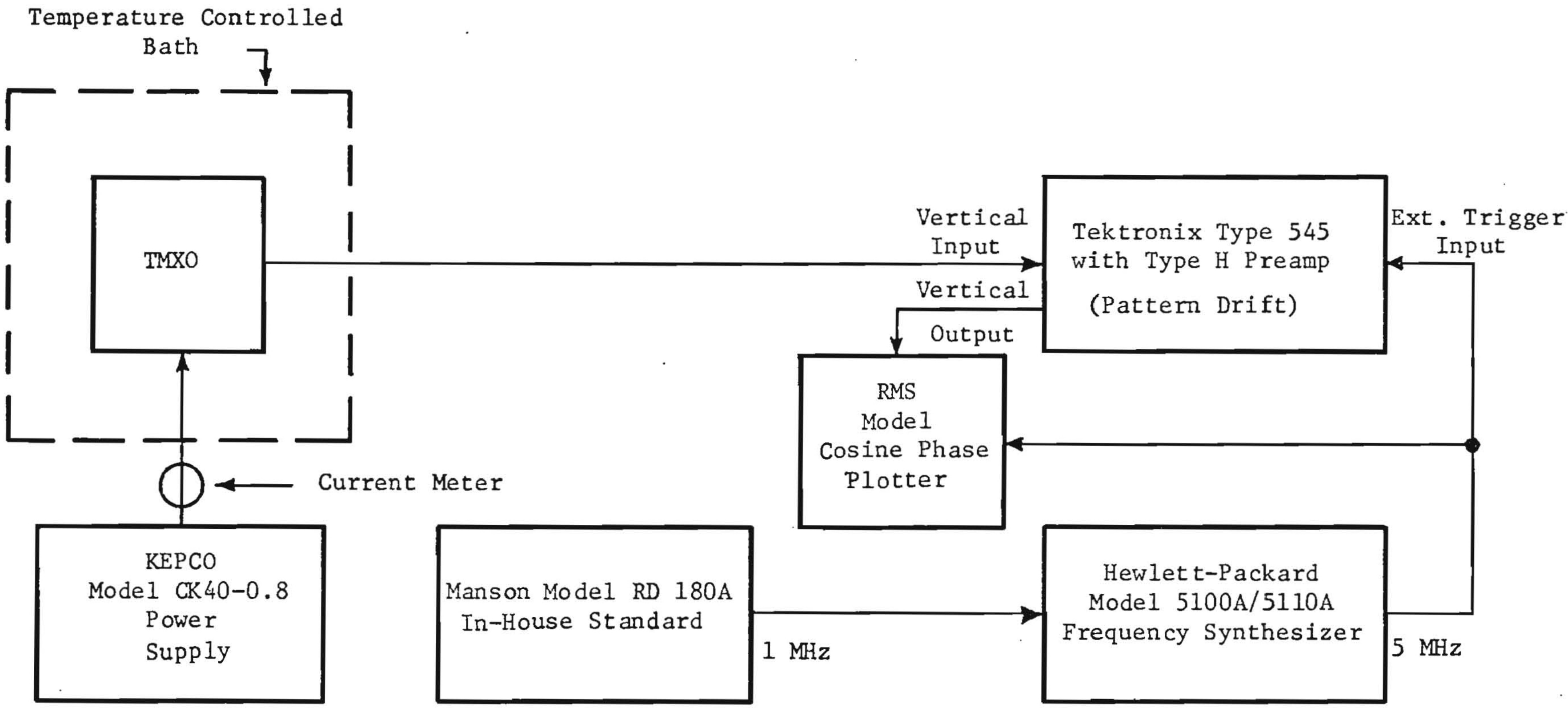


Fig. 20. Alternate system for making performance measurements. The frequency readout is analog. This method especially suited for long periods of operation with equipment unattended.

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 vibramatic 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.

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*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 R4 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.

The temperature overshoot during the third run swings through the UTP (region of minimum TCF) and returns back through the UTP to the operating temperature. During the time it takes for this to occur (a few seconds) the frequency changes are minimized for the temperature changes occurring due to the overshoot.

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

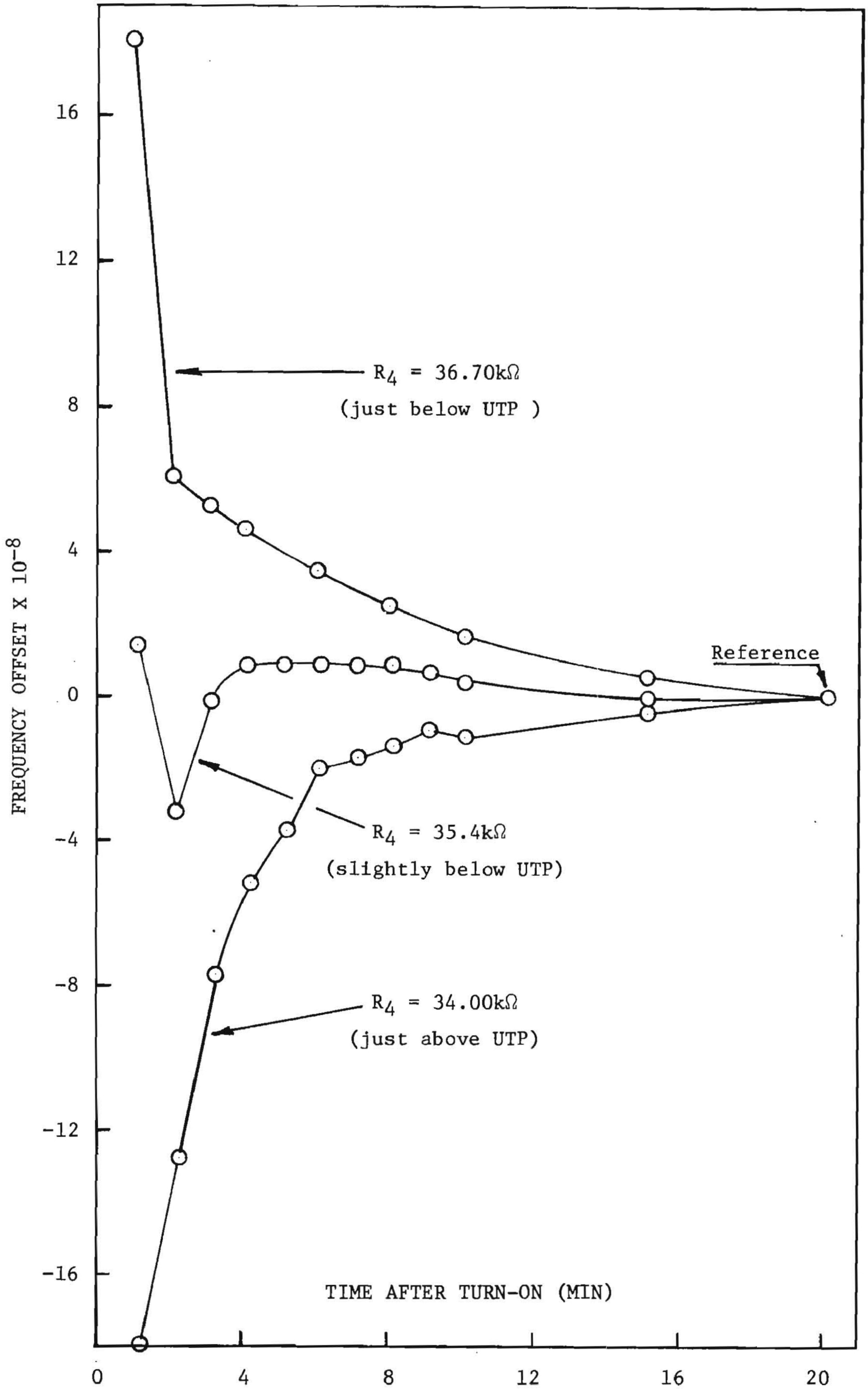

Fig. 21. Effect of temperature calibration on warm-up characteristics. TMXO-1 in air.

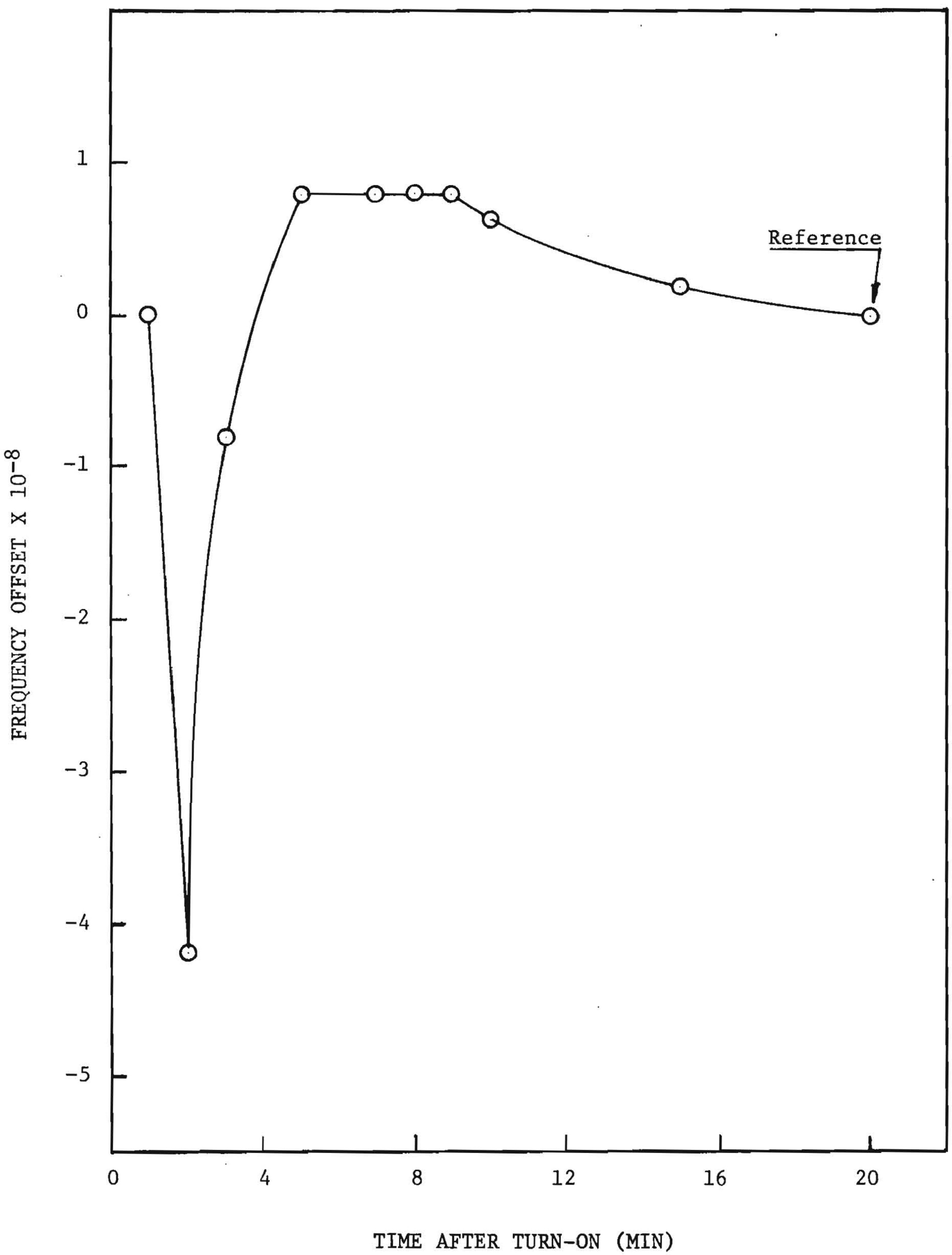

Fig. 22. TMXO-1 warm-up after temperature calibration. Oscillator circuit not attached to crystal. In air.

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 2.8×10^{-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 2.2×10^{-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.

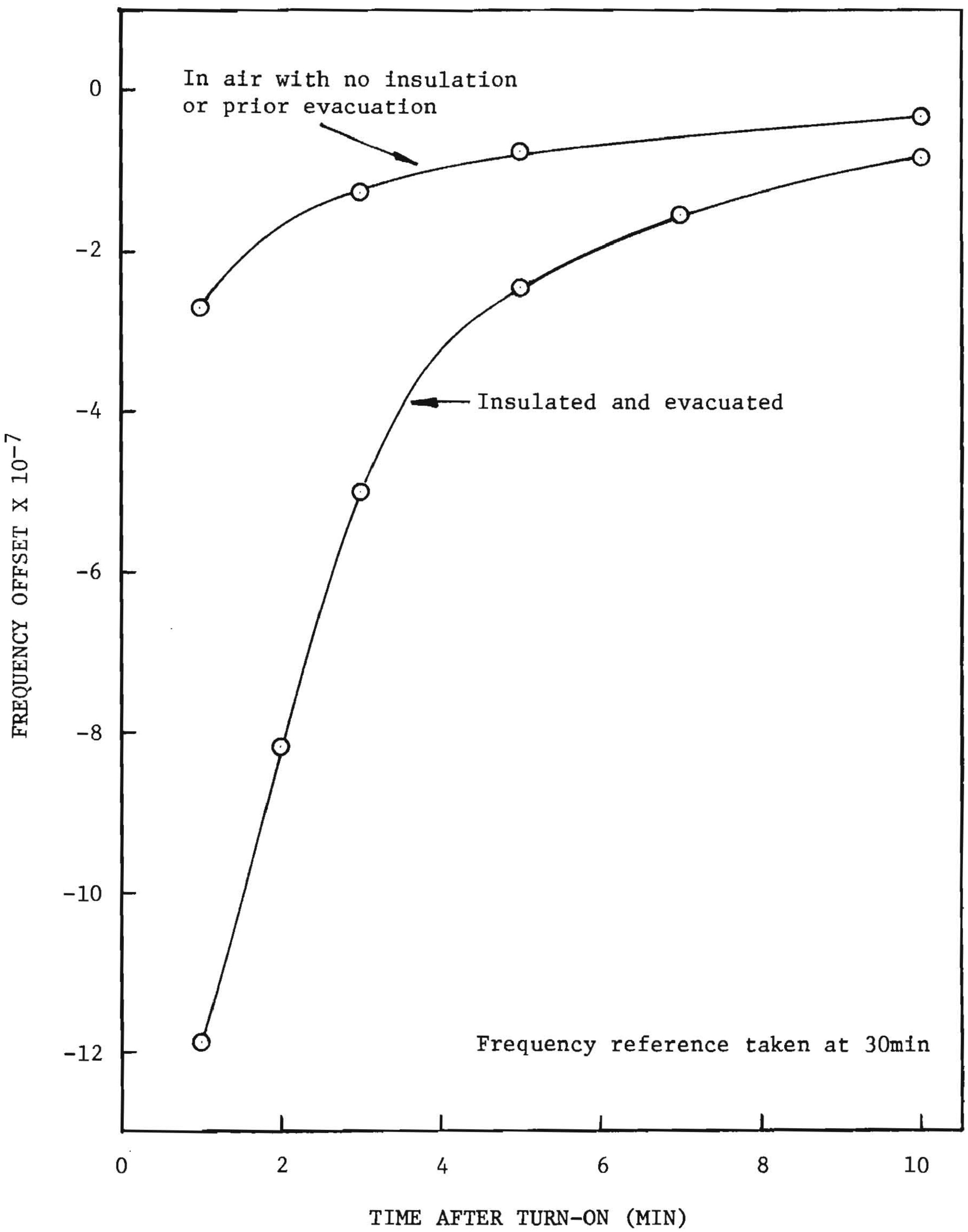

Fig. 23. TMXO-1 warm-up comparison at +25°C ambient before and after encapsulation.

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 VacIon pump. The base pressure during the following tests was 5 X 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 + 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°C, 30 sec at 24°C, and 10 sec at 75°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°C, +24°C, and +75°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°C, +24°C, and +75°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 ± 1.5 X 10^{-7}. The 25-turn potentiometer gives a resolution of 6 X 10^{-9}/turn and is adjustable to ± 1 X 10^{-10} of the final frequency. The range of ± 1.5 X 10^{-7} was needed, in lieu of the ± 1 X 10^{-8} requested, because of

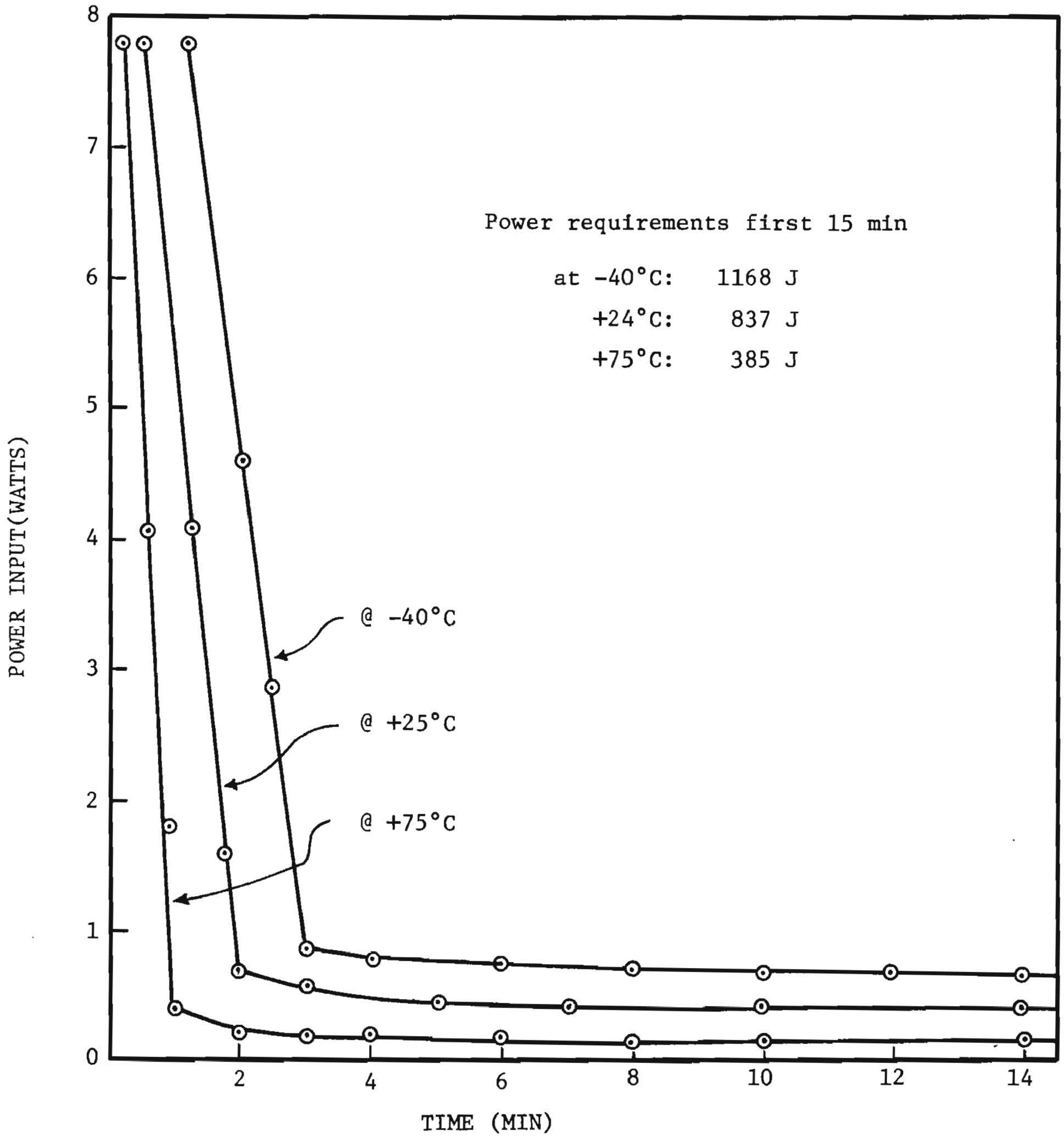

Fig. 24. Warm-up power profiles for first 15 minutes after turn-on. The technical guidelines requirement is 810 W-sec over the entire ambient temperature range.

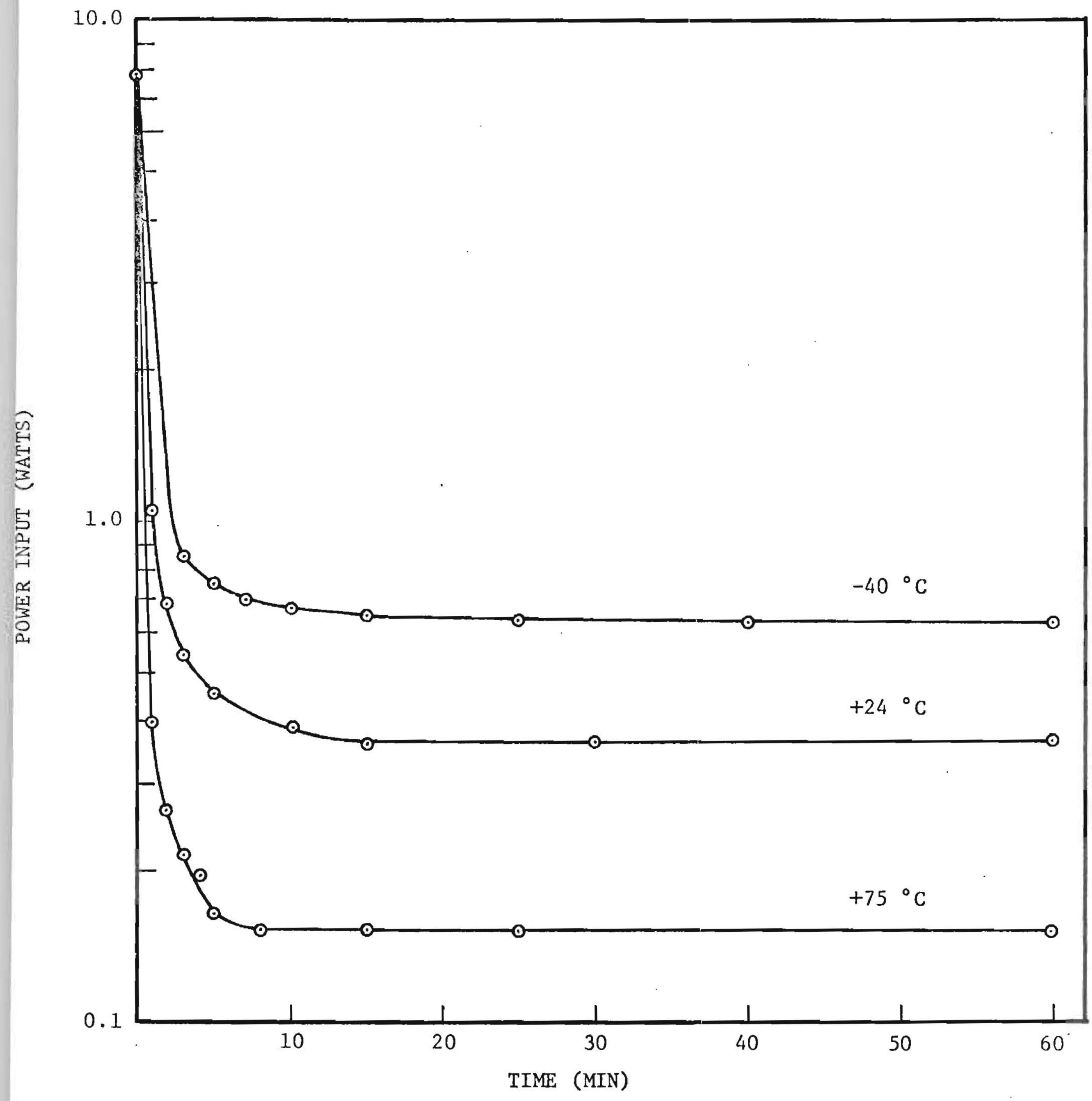

Fig. 25. Total operating power vs time for operating TMXO Model No. 1 in different ambient temperatures.

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 X 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.

$$F_{-40} = 5000000.323 \text{ Hz}$$

$$F_{+75} = 5000004.016 \text{ Hz}$$

$$\Delta F/F = + 7.4 \text{ X } 10^{-7}$$

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

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

k. Frequency Aging. The aging goal of $\pm$ 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. The short term frequency stability is approximately 4 X 10^{-10} 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 techniques 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.

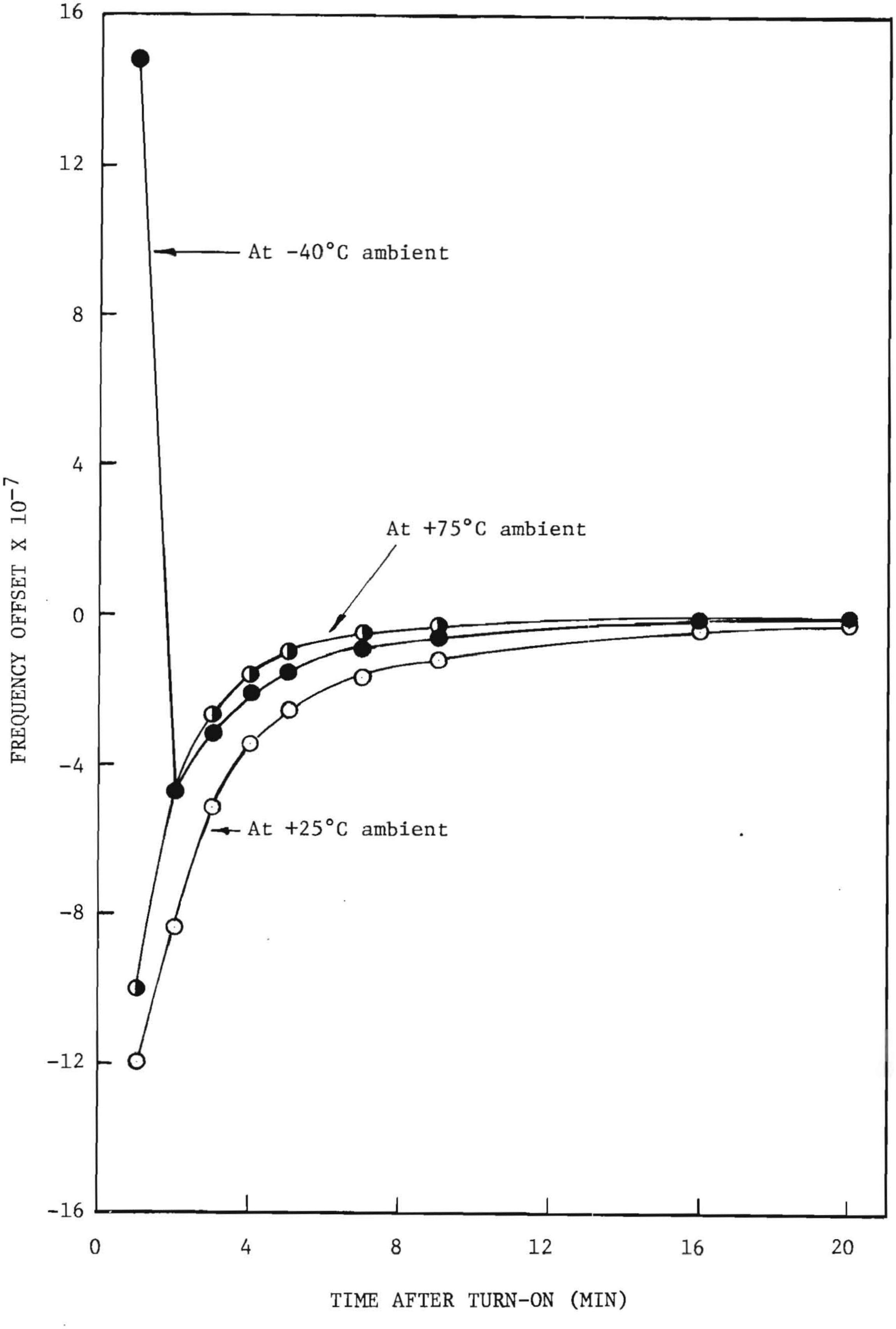

Fig. 26. TMXO-1 warm-up after encapsulation and evacuation to $<1X10^{-5}$torr.

		At -40°C	At 24°C	At 75°C
$\Delta F/F$ at 1 min after turn-on	=	$+ 1.5 \times 10^{-6}$	$- 1.2 \times 10^{-6}$	$- 9.96 \times 10^{-7}$
$\Delta F/F$ at 2 min after turn-on	=	$- 4.7 \times 10^{-7}$	$- 8.4 \times 10^{-7}$	$- 4.83 \times 10^{-7}$
$\Delta F/F$ at 4 min after turn-on	=	$- 2.1 \times 10^{-7}$	$- 3.5 \times 10^{-7}$	$- 1.63 \times 10^{-7}$
$\Delta F/F$ 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 outgassing.

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 Hz

Run No. 2: F = 5000000.339 Hz

Run No. 3: F = 5000000.302 Hz.

The maximum frequency deviation was 7.8×10^{-9}.

o. Output Voltage. The output voltage was measured at 177 mV rms across a load of $1000\angle 0°\ \Omega$.

p. Shock and Vibration. Since this model was tested while still attached to the small VacIon 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

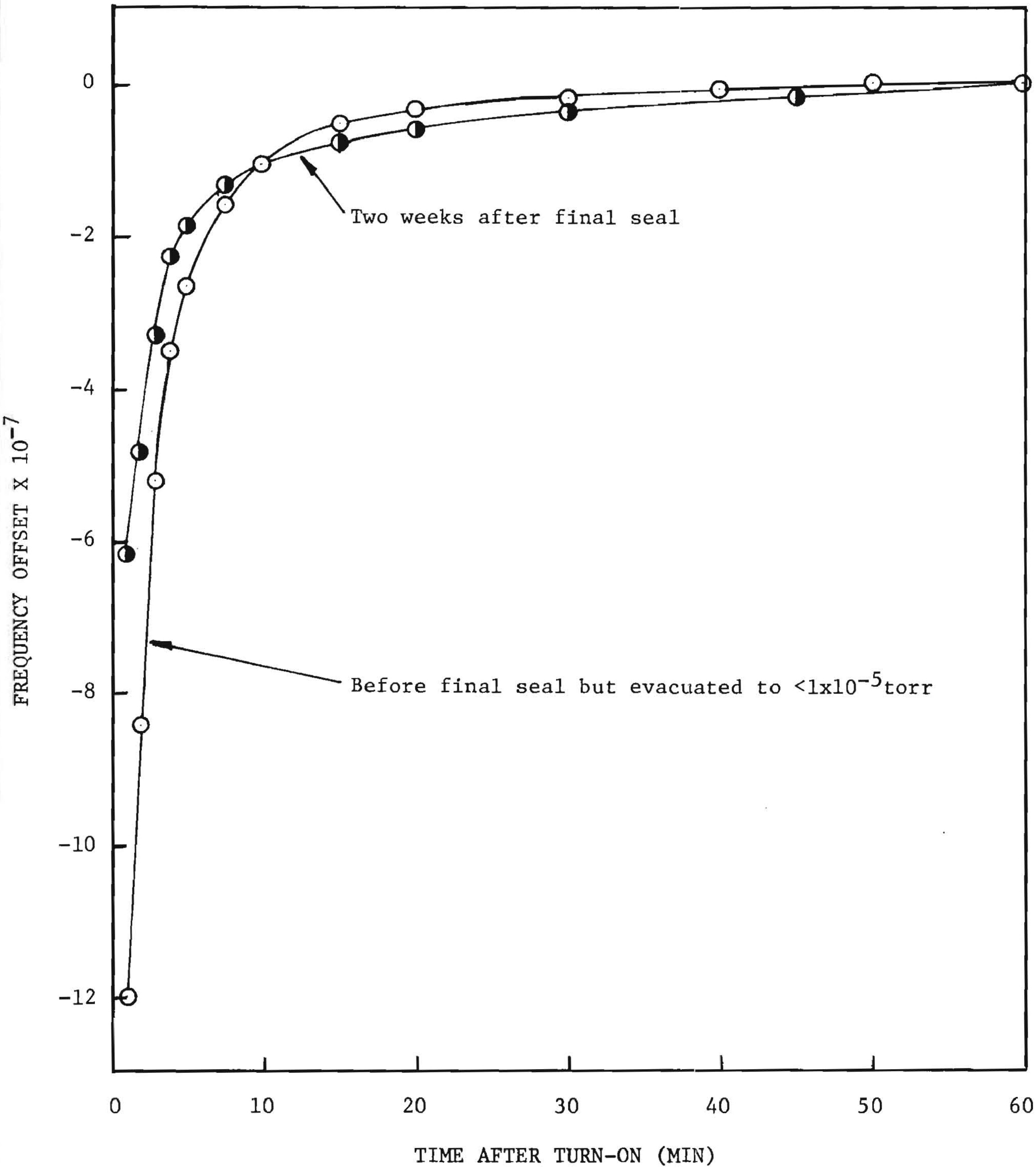

Fig. 27. TMXO-1 warm-up before and after final sealing.

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 kΩ. The second adjustment required an R_4 of 57.0 kΩ. 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 kΩ 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 3×10^{-6} torr. No leaks were detected initially. During later testing it became obvious 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.

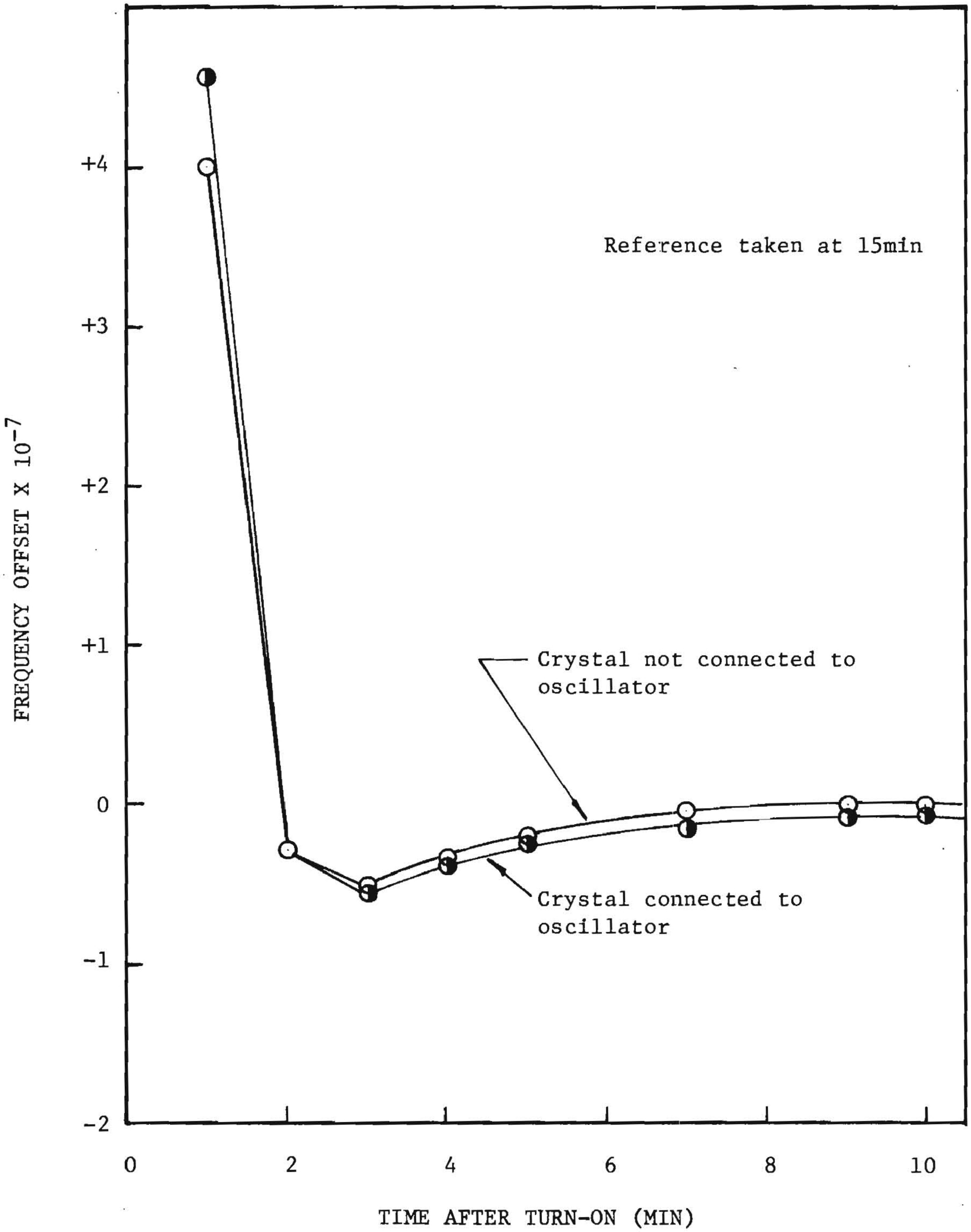

Fig. 28. TMXO-2 warm-up showing effect of oscillator circuitry.

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 in^3.

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.

Model No.	Highest Frequency	Lowest Frequency	ΔF/F
2	4999998.565	4999997.423	2.28×10^{-7}
3	4999999.439	4999998.663	1.55×10^{-7}

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.

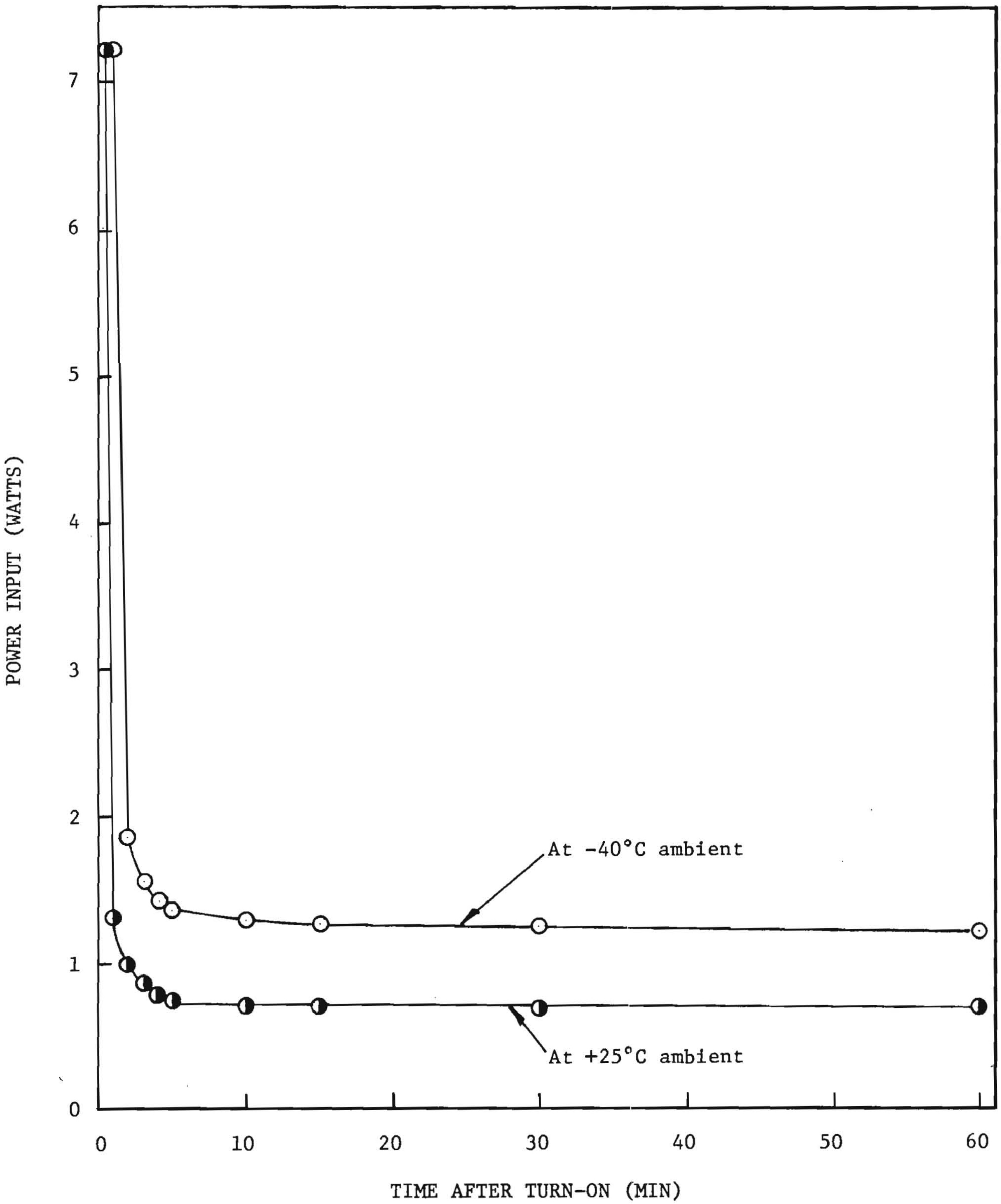

Fig.29. TMXO-2 input power requirements.

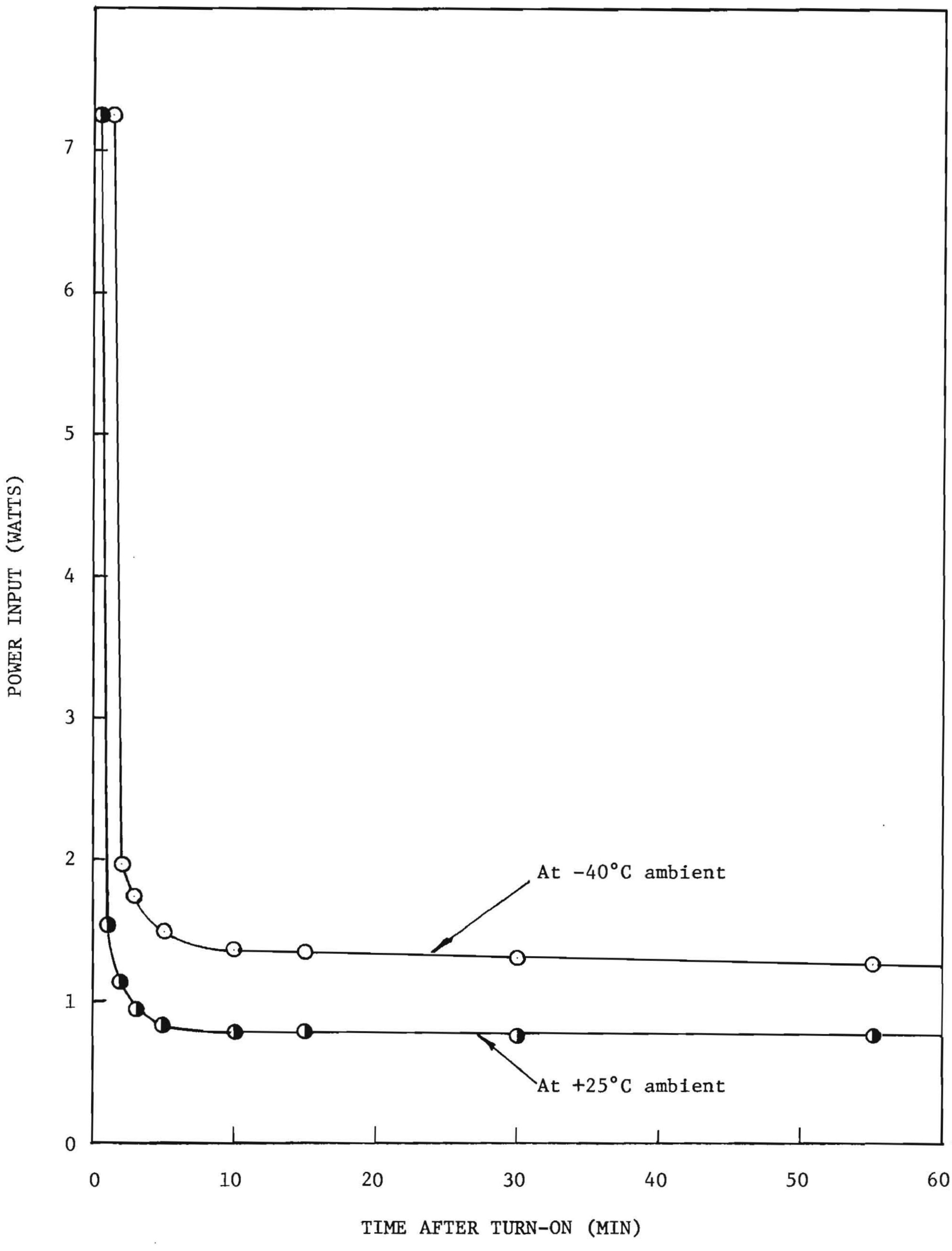

Fig.30. TMXO-3 input power requirements.

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:

$$F(-40°C) = 4999999.488 \text{ Hz}$$

Time at +75°C (min)	Frequency (Hz)
2	4999996.62
4	4999996.48
6	4999996.53
10	4999996.67
15	4999996.67

The frequency change after 15 minutes at +75°C is -5.64×10^{-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 -7.8×10^{-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

Load (Ω)	Frequency (Hz)	ΔF/F
$1000\,\vert\,\underline{0°}$	4999997.818	Reference
$1100\,\vert\,\underline{0°}$	4999997.773	-9.0×10^{-9}
$900\,\vert\,\underline{0°}$	4999997.928	$+2.2 \times 10^{-8}$
$1000\,\vert\,\underline{+20°}$	4999998.046	$+4.6 \times 10^{-8}$
$1000\,\vert\,\underline{-20°}$	4999997.838	$+3.8 \times 10^{-8}$

Note: Short-term frequency instabilities are large enough to bias above data.

Model No. 3

Load (Ω)	Frequency (Hz)	$\Delta F/F$	
$1000\vert\underline{0°}$	4999999.357	Reference	
$1100\vert\underline{0°}$	4999999.357	$<\pm 2 \times 10^{-10}$	(Resolution of measurement)
$900\vert\underline{0°}$	4999999.357	$<\pm 2 \times 10^{-10}$	
$1000\vert\underline{+20°}$	4999999.357	$<\pm 2 \times 10^{-10}$	
$1000\vert\underline{-20°}$	4999999.358	$+ 2 \times 10^{-10}$	

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

Model No.	$\Delta F/F$ 11.4 V	12.6 V
2	$+ 1.4 \times 10^{-9}$	0
3	$+ 9.2 \times 10^{-9}$	$- 6.4 \times 10^{-9}$

The reference frequency was taken at 12.0 volts.

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. 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 ($\sim 4 \times 10^{-10}$/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 $\pm 1 \times 10^{-11}$, 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

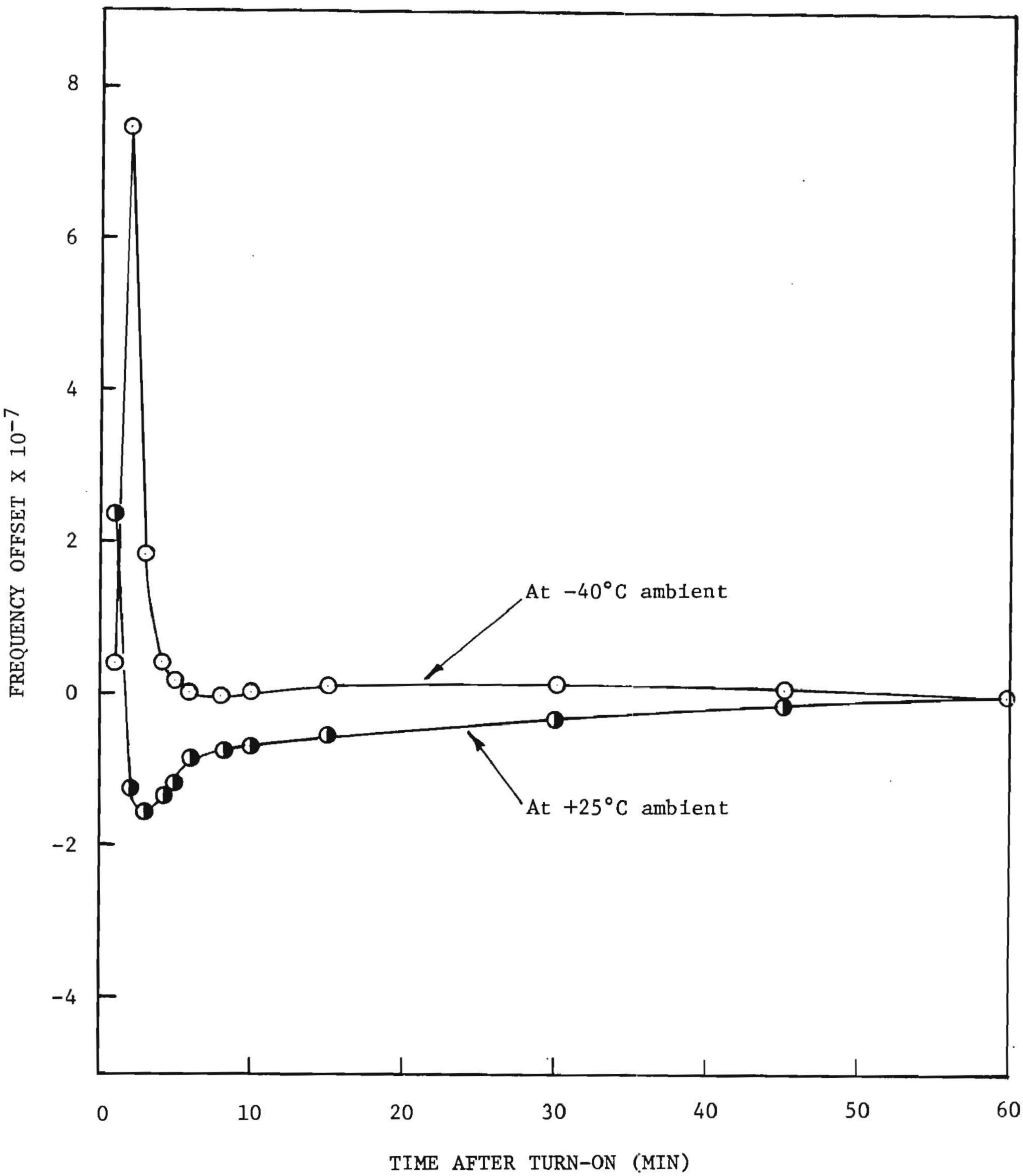

Fig.31. TMXO-2 warm-up after encapsulation.

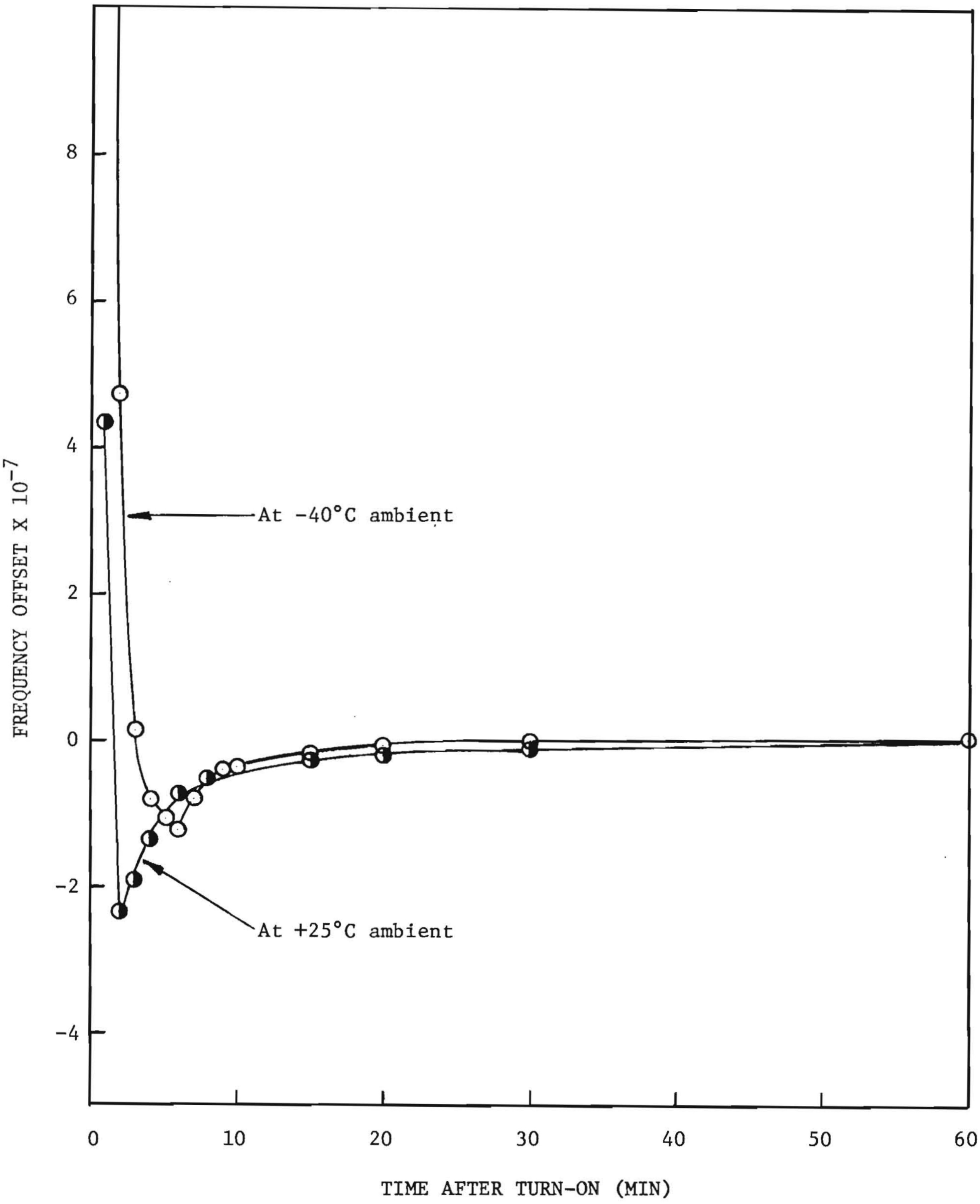

Fig.32. TMXO-3 warm-up after encapsulation.

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.

	Model No. 2		Model No. 3	
Time	-40°C	+25°C	-40°C	+25°C
1 min	$+4.0 \times 10^{-8}$	$+2.4 \times 10^{-7}$	$+2.1 \times 10^{-6}$	$+4.3 \times 10^{-7}$
2 min	$+7.5 \times 10^{-7}$	-1.3×10^{-7}	$+4.7 \times 10^{-7}$	-2.4×10^{-7}
4 min	$+4.2 \times 10^{-8}$	-1.4×10^{-7}	$+8.3 \times 10^{-7}$	-1.4×10^{-7}
15 min	$+9.8 \times 10^{-9}$	-5.4×10^{-8}	-1.9×10^{-8}	-2.7×10^{-8}

n. Frequency Recovery at -40°C Ambient. Model No. 2 incurred a frequency offset of -4.2×10^{-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 $1000\underline{|0°}\ \Omega$.

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 leeching 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, Q_2, 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 Q_2 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 Q_2 of the control circuit might be the problem. The method of biasing Q_2 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

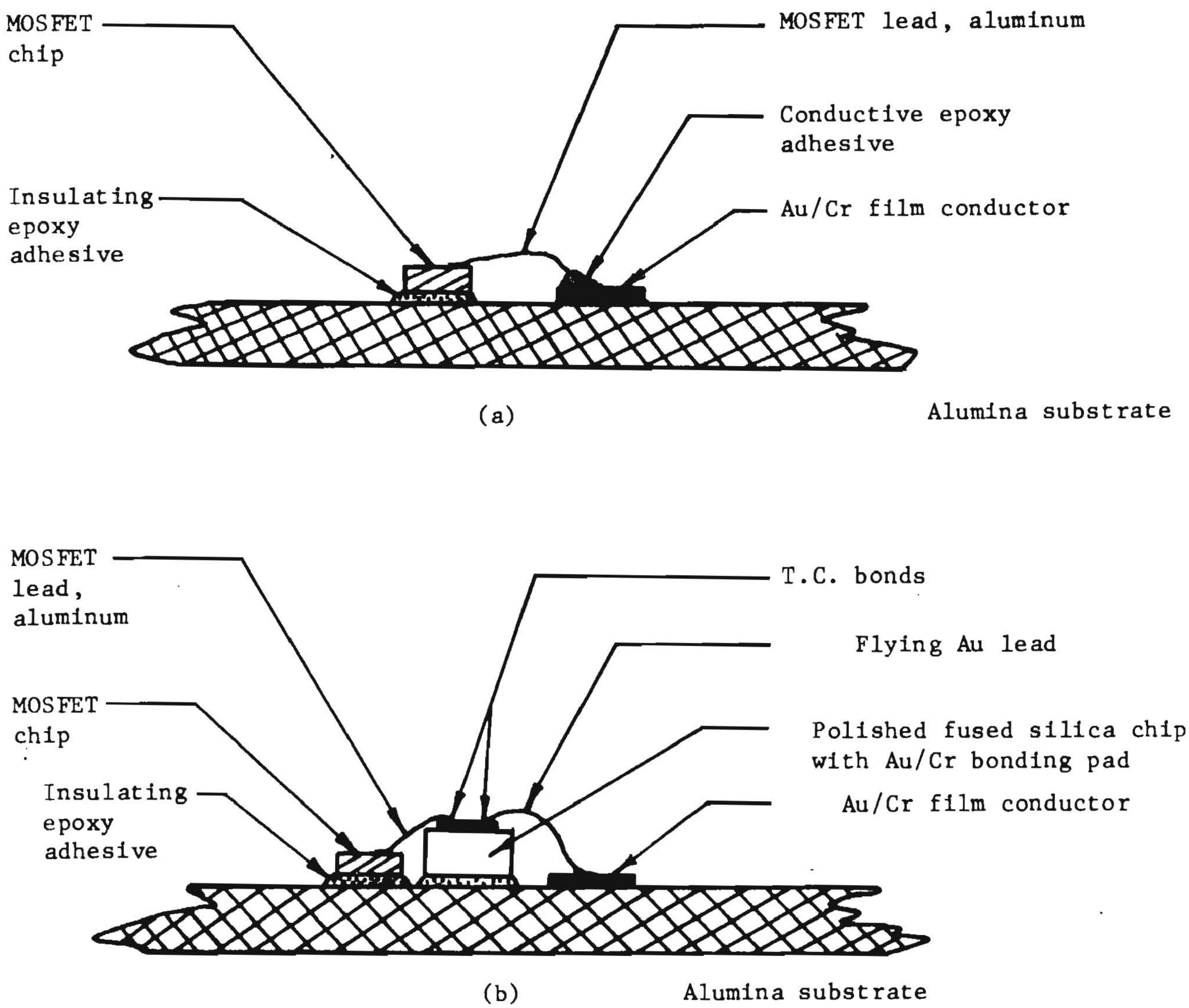

Fig. 33. Sketch illustrating attachment of MOSFET chip to microcircuit board; (a) initial manner of attaching MOSFET chip to circuit board, (b) modification of attaching MOSFET to eliminated shorting of leads to edge of chip.

many hours of operation without properly heat sinking Q_2. Thus there is lack of conclusive evidence that Q_2 is experiencing thermal runaway 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 Q_2 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 runaway 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 isothermal 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^{-4} 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 materials are the plastic foam insulators which have K values of about 2 X 10^{-4}W cm/cm$^2\Delta$T. 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/cm$^2\Delta$T.

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/cm^2-°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.

Insulating Material	Pressure	Operating Power
None	ATM	900 mW
None	10^{-6} torr	444 mW
CAB-O-SIL	ATM	660 mW
CAB-O-SIL	10^{-6} torr	242 mW
NRC-2	ATM	750 mW
NRC-2	10^{-6} torr	150 mW

*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[5]. 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

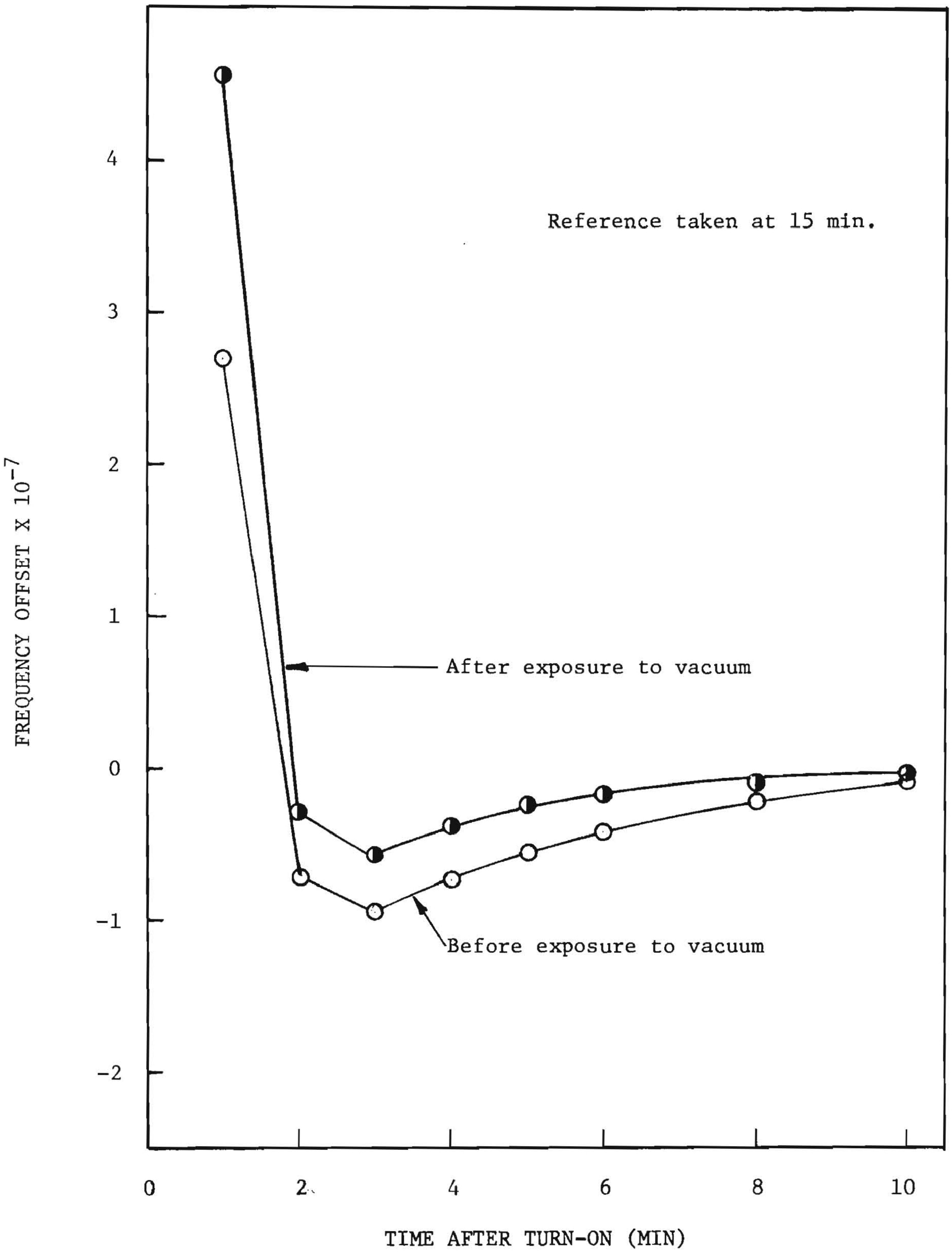

Fig.34. TMXO-2 warm-up comparison before and after unit exposed to vacuum.

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 2×10^{-6} end-to-end with a 1×10^{-8} resolution and the second of about 1×10^{-8} end-to-end with a 1×10^{-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.

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13. ABSTRACT

The purpose of this work was to develop an experimental tactical miniature crystal oscillator (TMXO) in a 5 in^3 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 $\pm 1 \times 10^{-7}$ 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.

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14 KEY WORDS	LINK A		LINK B		LINK C	
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Microcircuits						
Fast warm-up						
Low power						
Low aging						
Minimum retrace						