THE UNIVERSITY OF MICHIGAN
COLLEGE OF ENGINEERING
Department of Electrical Engineering

Task 3

Progress Report No. 1

Period Covering October 3, 1958, to January 31, 1959

SPACE PHYSICS COMMUNICATIONS

L. W. Orr P. G. Cath

UMRI Project 2816-3

under contract with:

DEPARTMENT OF THE ARMY
BALLISTICS RESEARCH LABORATORY
PROJECT NO. DA-5B03-06-011-ORD (TB 3-0538)
CONTRACT NO. DA-20-018-509-ORD-103
ABERDEEN PROVING GROUND
ABERDEEN, MARYLAND

administered by:

THE UNIVERSITY OF MICHIGAN RESEARCH INSTITUTE ANN ARBOR

February 1959

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ABSTRACT

The task assignments, personnel, and meetings of Task 3 for the period October 3, 1958, to January 31, 1959, are reviewed. Transistorized 36-Mc oscillator circuits and frequency-stability measurements are presented. Means for thermal stabilization of the rocket-borne beacon oscillator are discussed, and an analysis of thermal design using the heat-of-fusion method is presented.

1. INTRODUCTION

Task 3 under the contract is to be concerned with the development of a rocket-borne radio-frequency transmitting system and the assembly of ground-station receiving equipment with the general objective of tracking, telemetry, and capability for the measurement of ionospheric electron density through the use of the two-frequency technique. This program will be reviewed quarterly in formal progress reports. The current report covers the interval from October 3, 1958, to January 31, 1959.

The specific efforts under Task 3 are to be directed toward the following:

1. Study of instrumentation necessary to transmit a single-frequency low-power CW signal from the high-altitude rocket probe being developed under Task 4. The frequency stability of the transmission should be better than one part in 10^7 during flight.

2. The construction of two nose-cone single-frequency beacons for the firing of the two rockets of Task 4 at Wallops Island. If a two-frequency system can be developed in time, this is preferable. If the two-frequency system is developed, the stability requirement decreases to one part in 10^6.

3. The assembly at the contractor's plant of the necessary GFE equipment for carrying out the frequency tracking and data recording of the Wallops Island firing of Task 4.

4. In cooperation with the Ballistics Research Laboratories, the specifications for the rocket-borne antenna systems for the Wallops Island firings of Task 4 will be furnished and the systems will be tested.

5. The ground equipment will be operated in connection with the Wallops Island firings for the recovery of the transmitted signal.

2. PERSONNEL

Name	Title	
Lyman W. Orr	Task Engineer	Full-Time
Pieter G. Cath	Graduate Research Assistant	Part-Time
Wilbur Nelson	Technician	Part-Time
N. W. Spencer	Project Supervisor	Part-Time

3. MEETINGS AND REPORTS

On October 3, 1958, Messrs. N. W. Spencer and L. W. Orr visited the Ballistics Research Laboratories to discuss Task 3 with Messrs. W. Berning, G. DeBey, and J. Mester.

On December 4, 1958, Messrs. W. Berning and H. Cobb of BRL and Mr. Skeffington of the Detroit Ordnance District Office visited Ann Arbor to discuss the specific task assignment with University of Michigan personnel.

On December 15, 1958, Messrs. L. W. Orr and N. W. Spencer visited the Ballistics Research Laboratories to discuss specific details of the task with BRL personnel. Ground-station system planning was discussed with Messrs. Berning, Richard, DeBey, Patterson, Zancanata, and Wilson. Airborne antenna design and power level were discussed with Mr. Richard.

No reports were issued during the interval.

4. TRANSISTOR OSCILLATOR CIRCUIT DEVELOPMENT

4.1. DEVELOPMENT OF OSCILLATOR CIRCUIT

In the original discussion about the present task, Mr. C. Wilson of BRL recommended a transistor oscillator circuit having very good frequency stability. This circuit, called circuit "A," is shown in Fig. 1. Mr. Wilson loaned one of his oscillators to us, and our first task was to make a copy of this oscillator and study its behavior. This study revealed that oscillator A (Fig. 1) is quite sensitive to changes in bias voltages.

In an effort to reduce this sensitivity and also to reduce the number of components, circuit A was modified. The results of these modifications, circuit B and circuit C, are shown in Figs. 2 and 3, respectively. That circuits B and C are actually modifications of circuit A can be seen from the a-c vector diagram for the bridge circuit of oscillator A. In this vector diagram (Fig. 4), the letters denote the voltages at points A, B, C, and D with respect to ground (0), as indicated in Fig. 1. In drawing the vector diagram it was assumed that the impedances of capacitances C_A and C_B are smaller than the series resistance of the crystal. Although this assumption is not justified, it demonstrates very nicely the principle of operation of the circuit.

Assuming that the phase shift in the transistor does not differ appreciably from 180°, the condition for oscillation is that the voltage OD is 180° out of phase with voltage OC, while at the same time the voltage gain in the transistor is larger than OC/OD. The voltage OD will be out of phase with OC at the frequency ω_0, which is the series resonant frequency of the crystal. When the fre-

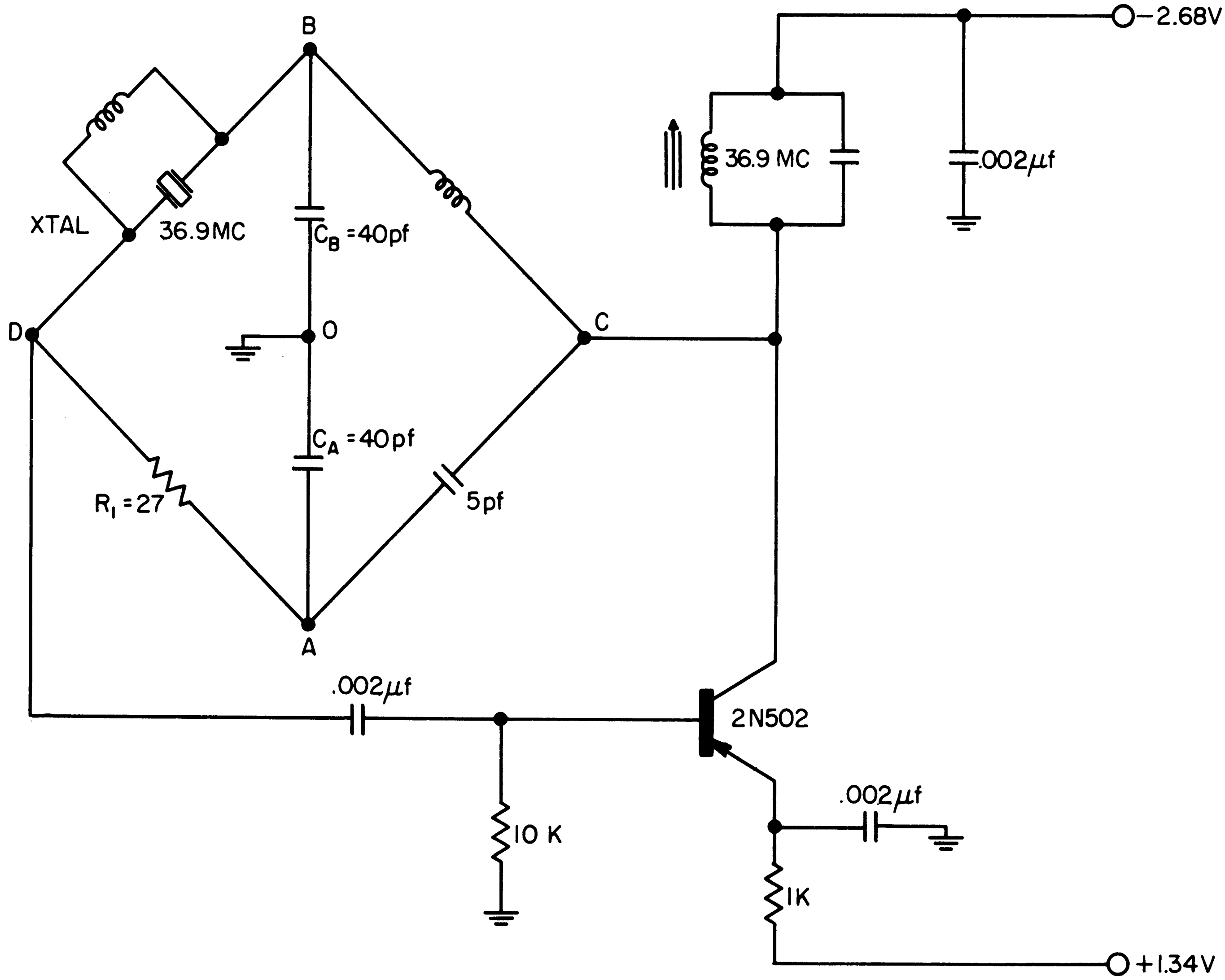


Fig. 1. Original oscillator circuit A.

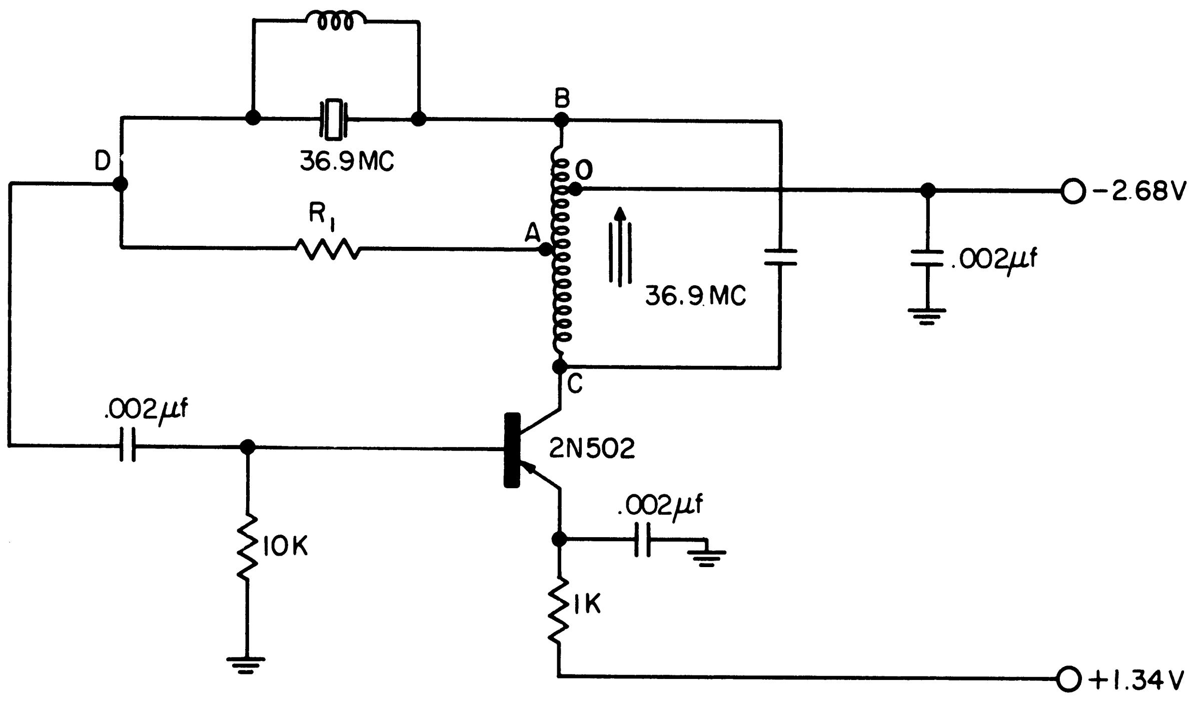


Fig. 2. Oscillator circuit B.

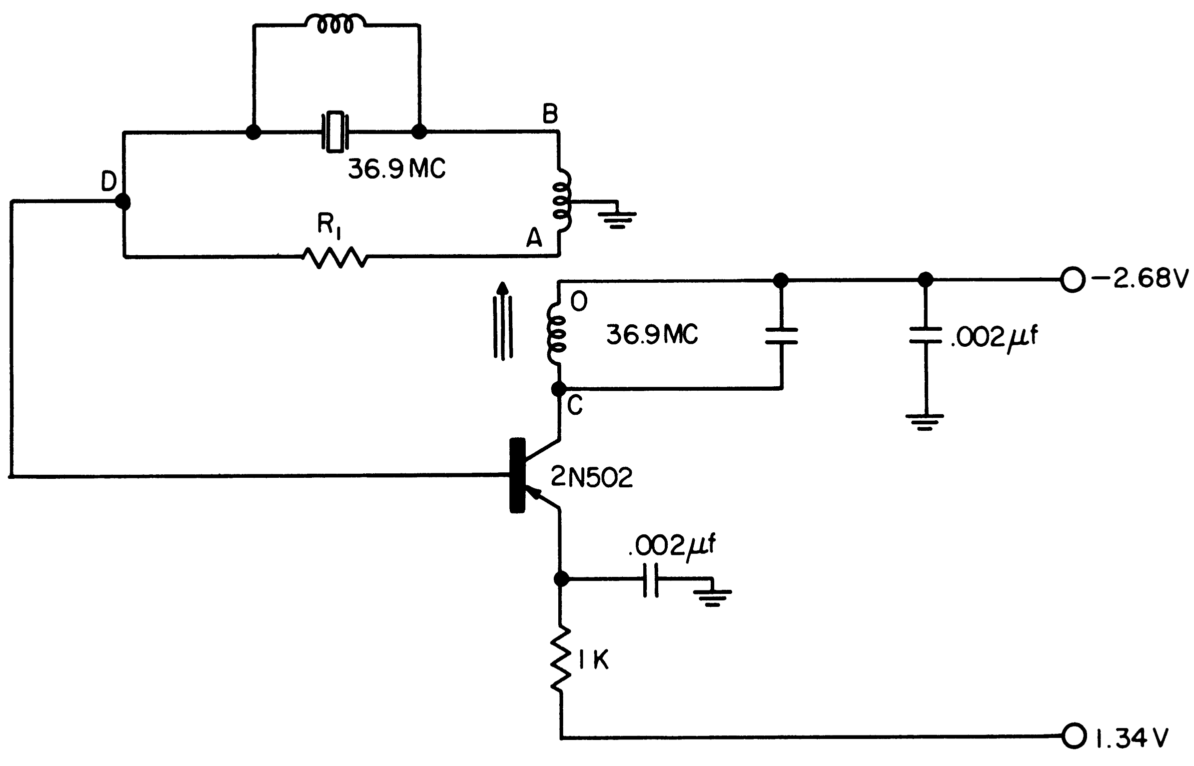


Fig. 3. Oscillator circuit C.

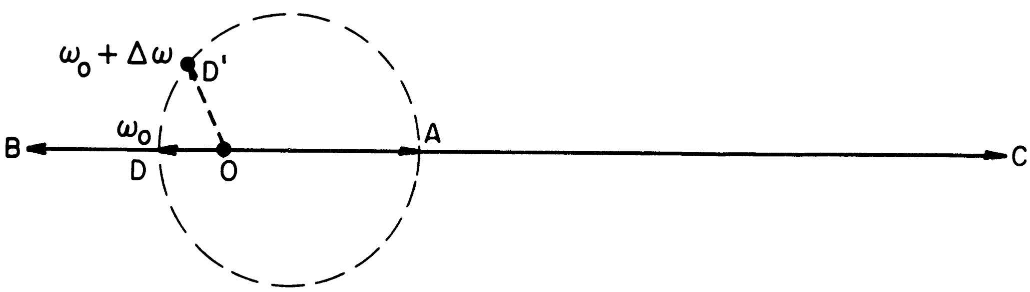


Fig. 4. Oscillator vector diagram.

quency changes, the output voltage of the bridge changes both in magnitude and in phase as indicated in Fig. 4 by the point D'. The faster the phase of voltage OD changes as a function of frequency, the more stable will be the frequency of the oscillator. It is apparent that this fast rate of change can be achieved by designing the oscillator so that the point D is as close to point O as possible. This can be done by a suitable choice of resistor R_1 (Figs. 1, 2, and 3). Of course the voltage gain in the transistor must always be larger than OC/OD, which is the reason why OD cannot be made arbitrarily small.

Instead of using a bridge-type circuit to obtain the two voltages OA and OB, that are 180° out of phase, circuit B uses taps on the winding of the tank coil, and circuit C uses a separate winding, magnetically coupled to the tank circuit. Accordingly, oscillators B and C have the same vector diagram as circuit A.

Not only do the circuits B and C have fewer components, but their sensitivity due to bias changes is also much smaller than that of circuit A. The frequency shift of circuit A due to changes in collector voltage was measured to be in the range of 40 to 260 cps per volt, at a nominal frequency of 36.940 Mc. The shift of circuit A due to changes in emitter current was found to be between 0 and 130 cps per mA, depending on the actual bias point. Circuits B and C show considerable improvement in this respect. The frequency sensitivity to bias changes for both circuits B and C is in the range of 0-55 cps per volt for changes in collector voltages, and 0-30 cps per mA for changes in emitter current. The change in frequency as a function of bias point is shown in Fig. 5, which represents a typical behavior for both circuit B and circuit C.

Figure 6 shows the change in frequency due to changes in temperature. The solid line indicates the frequency shift when all components of the oscillator, including, of course, the crystal, are placed in the oven. The broken line shows what happens to the frequency when only the crystal is subjected to changes

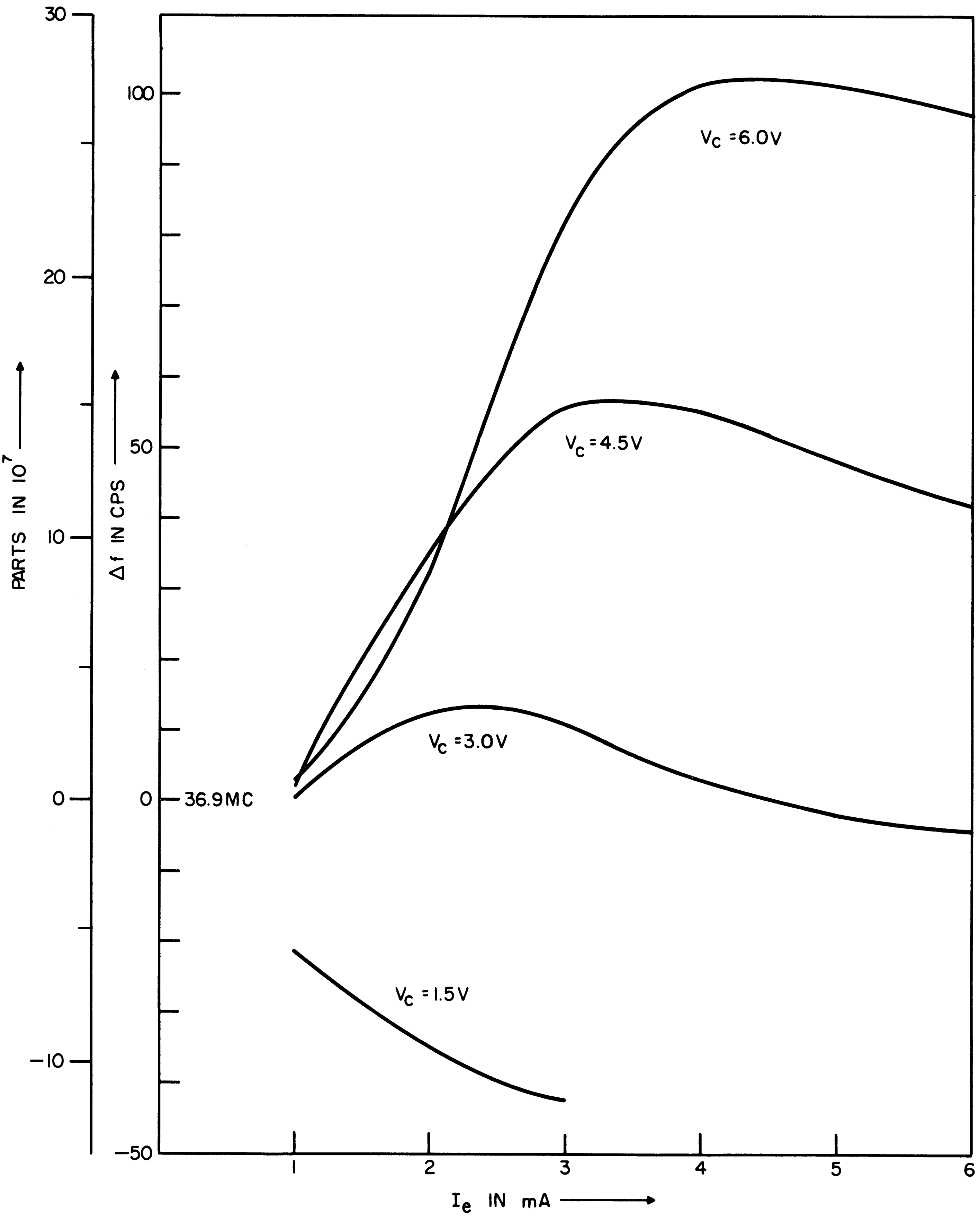


Fig. 5. Frequency shift due to bias changes.

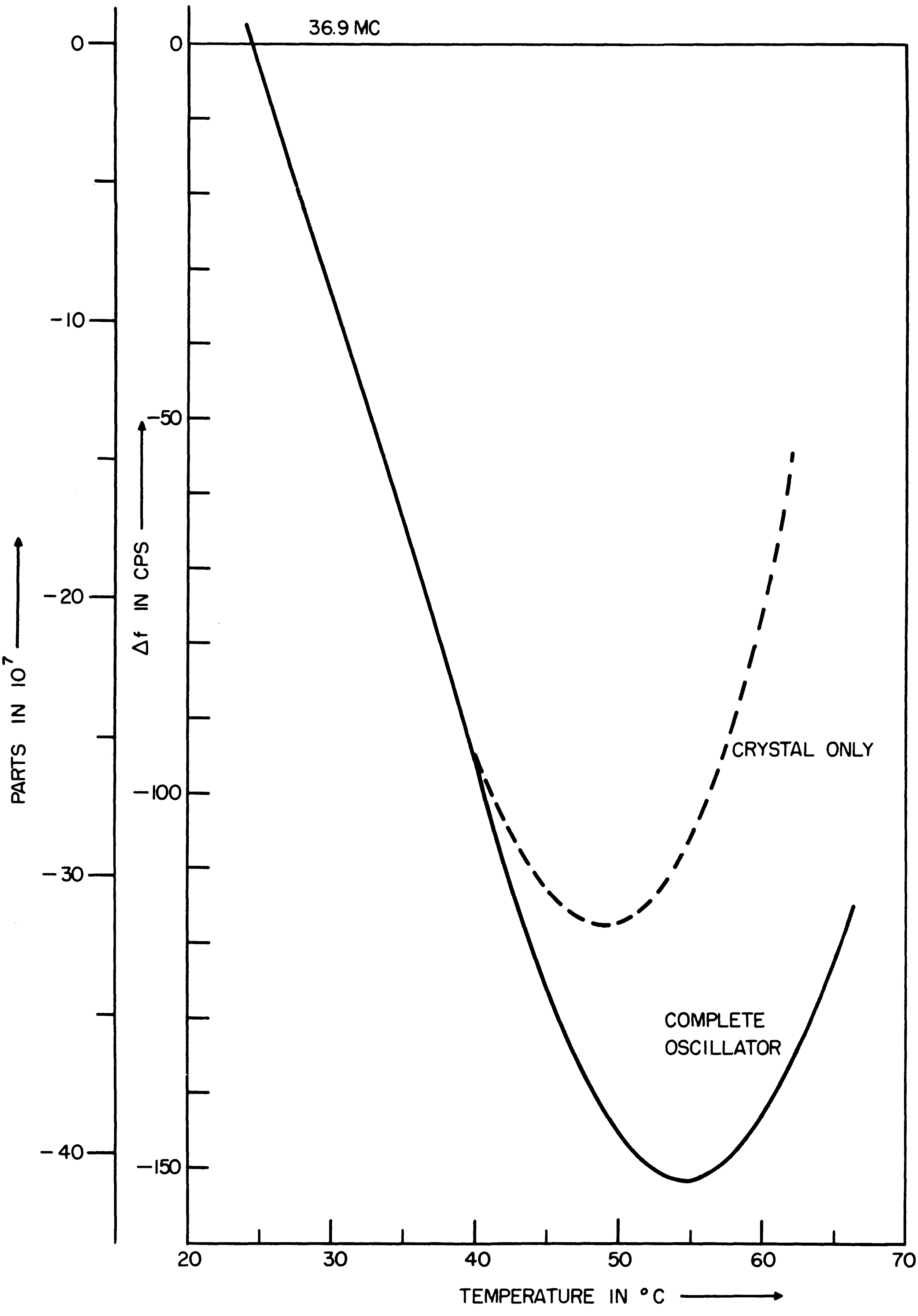


Fig. 6. Frequency shift due to temperature changes.

in temperature, while the other components remain at room temperature. It can be concluded from Fig. 6 that below 40°C the temperature of the other components has very little effect on the frequency.

The point at which the temperature coefficient is zero is determined by the cut of the individual crystal. It depends upon the orientation of the crystal surfaces with respect to the crystal planes. For high-frequency crystals that have to be very thin, it becomes virtually impossible to orient the crystal accurately enough during grinding to be able still to control the temperature at which the temperature coefficient is zero. This temperature is therefore different for each individual unit. The units that were used in our oscillators were supplied on special order by McCoy Electronics Company.

Figure 7 shows top and bottom views of the internal construction of one of the oscillators that were built on this project (circuit C). It is enclosed in a cubical metal case similar to the original BRL oscillator, but provision is made for external battery connections.

4.2. MEASURING PROCEDURE

The frequency measurements were made according to the block diagram shown in Fig. 8. The signal from the oscillator under test is compared with that of the reference oscillator. The beat note appears as an audio signal at the output of the receiver.

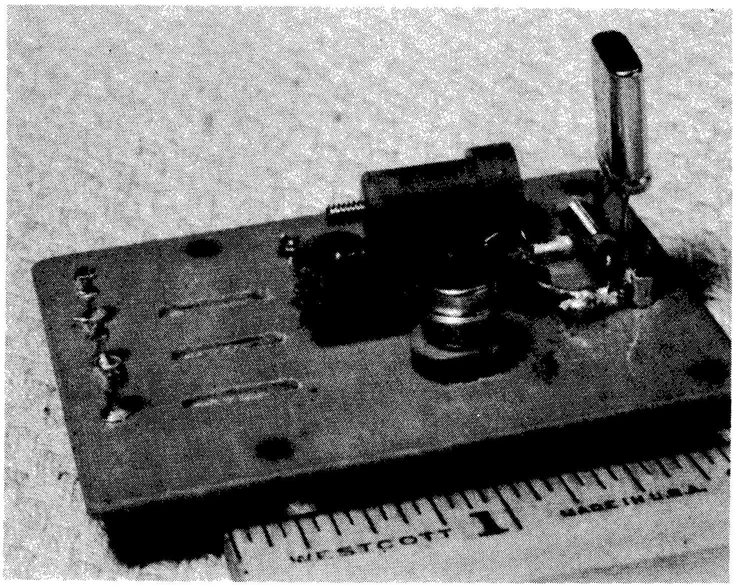
The accuracy of this method depends primarily on the quality of the reference oscillator. To make sure that frequency drift of the reference oscillator will not affect the measurements, one always returns to the starting point.

As the oscillators were improved, the reference oscillator was replaced by the best available oscillator, and presently an oscillator of type C is used as a reference. The frequency of the reference oscillator was raised by connecting a 40 μμf capacitor in series with the crystal. This was done to make the beat note sufficiently high in frequency to pass through the audio amplifiers of the R220/URR receiver.

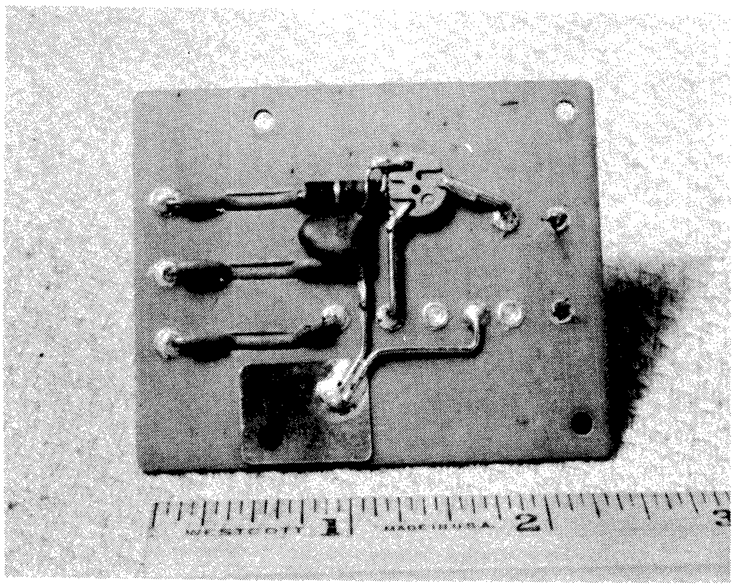
The reference oscillator is powered by a 6-volt storage battery to minimize drift due to changes in bias point. Drift due to temperature changes was minimized by placing the oscillator in a temperature-controlled oven. The circuit of the oven control[1] is shown in Fig. 9. A thermistor is used as the temperature-sensitive element.

Although no reliable frequency standard is available to test the stability of our reference oscillator, we have reason to believe that its stability is better than 1 part in 10^7 per week.

It remains to be pointed out that with the present arrangement it is not possible to make absolute frequency measurements.



TOP



BOTTOM

Fig. 7. Top and bottom views of the oscillator type C.

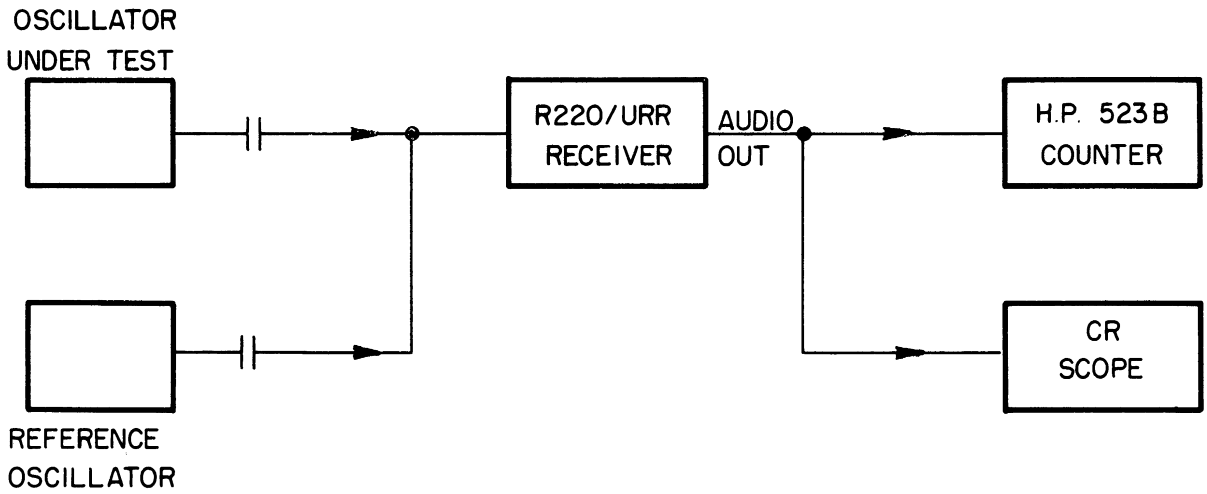


Fig. 8. Block diagram for frequency measurements.

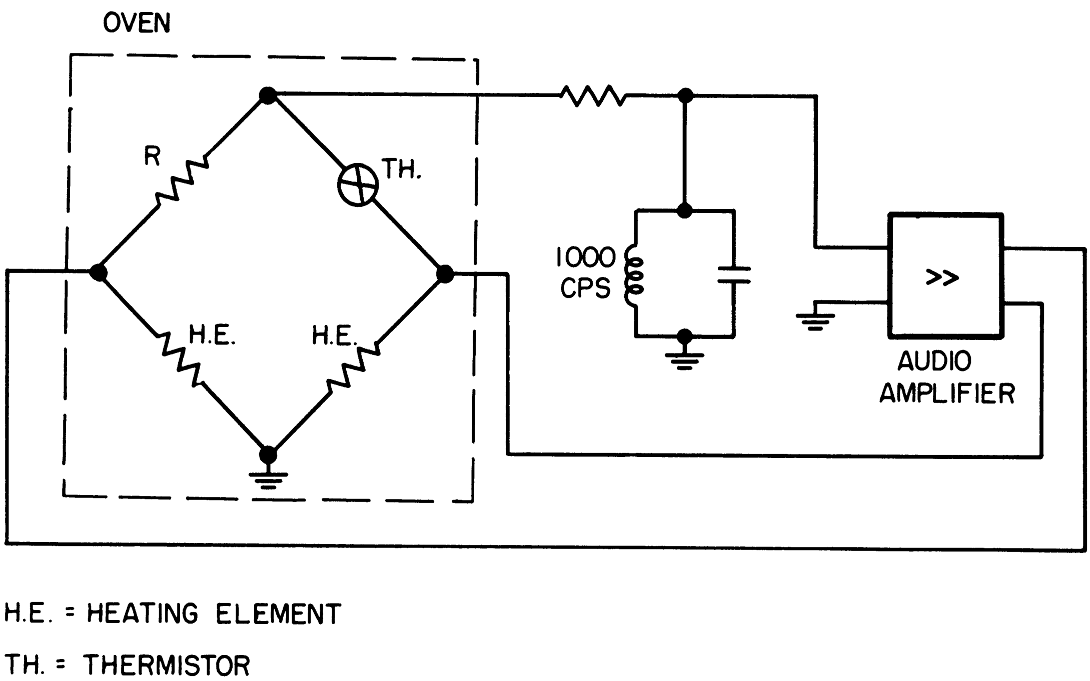


Fig. 9. Oven control circuit.

4.3. RADIO-FREQUENCY OUTPUT STAGE

Preliminary experiments were started to study the problems involved in the construction of a final stage capable of delivering between 100 and 500 mw of radio-frequency power to the antenna.

The 2N502 transistors used for the oscillators were found to be unsuitable for this purpose. The 2N502 is very sensitive to overload, since the rated maximum collector dissipation is only 60 mw. The dissipation in the base and the emitter also has to be taken into account. The emitter of the 2N502 transistor was found to overload. For these reasons, the experiments had to be suspended until better transistors are obtained. Texas Instrument 2N1143 transistors were ordered; these have a maximum collector dissipation of 750 mw and an alpha cut-off frequency of 480 Mc.

5. THERMAL STABILIZATION

As previously noted, the frequency stability of the flyable beacon oscillator is primarily a function of the temperature stability of the crystal holder and the thermal characteristic of the crystal. It is expected that, using special crystals furnished by McCoy Electronics Co., stability requirements of a few parts in 10^8 may be met by controlling the temperature to 0.1 to 0.2°C.

Considerable aerodynamic heating of the nose cone is expected in the early part of the flight, while radiation cooling will occur during the remainder. Since no data are available on nose-cone interior temperatures of the sort to be used in the 1000-mile probe, it will be assumed that the interior temperature will not exceed the limits of 100°C and 5°C. Conservative design will be such that crystal temperature will be maintained between the specified limits in an environment of either 100°C for 20 minutes or 5°C for 20 minutes.

5.1. OPERATING TEMPERATURE

The choice of operating temperature is a compromise between the less desirable crystal characteristics at higher temperatures and the desirability of operating above any expected ambient temperature on the ground, so that no refrigerant is required to prepare for takeoff. An operating temperature in the range 35°C to 45°C is considered desirable.

5.2. MEANS FOR TEMPERATURE CONTROL

Several means available for temperature control are:

(a) Thermostat.
(b) Inverse Peltier Thermojunctions.
(c) Large Thermal Mass.
(d) Heat of Vaporization.
(e) Heat of Fusion.

Temperature control by thermostat and heater requires the selection of an operating temperature which will always be above the ambient. Since an operating temperature in excess of 100°C, a chosen limit, is undesirable, this means must be abandoned.

Inverse Peltier Thermojunctions are available for both heating and cooling by means of current reversal. Some commercial units are available[2] but the efficiency of such units, at least as reported in unclassified literature, is so low as to be impractical for research rocket instrumentation with limited power resources.

Use of heat of vaporization is not practical because of the high sensitivity of the boiling point to pressure. Hence this would involve trading the problem of temperature control for one of pressure control.

The large-thermal-mass and the heat-of-fusion methods will be discussed in some detail. The former is characterized by a slowly varying temperature, while in the latter the temperature is held constant.

5.3. LARGE THERMAL MASS

Temperature control is most simply accomplished by a large mass in an insulating blanket. Although the temperature will vary slowly, the method succeeds provided the variation stays within specified limits. The spherical geometry illustrated in Fig. 10 is the most efficient, since it maximizes the volume-to-surface ratio. Here the central sphere of radius r_o is a metallic container for the oscillator while also serving as a heat sink at temperature T_o. The insulating blanket of radius r_1 retards the heat flow from the environment, at temperature T_1, into the sphere. The curve illustrates the temperature distribution at equilibrium.

When $T_1 > T_o$, heat is slowly gained by the sphere. Its temperature rise rate, T_o, is given by

$$T_o = \frac{3K(T_1 - T_o)}{r_o^2 (1 - \frac{r_o}{r_1})\, h_v} \quad (°C\ min^{-1}) \quad , \qquad (1)$$

where K = heat conductivity of blanket material and

h_v = volumetric heat of the sphere material (calories cm^{-3} $°C^{-1}$).

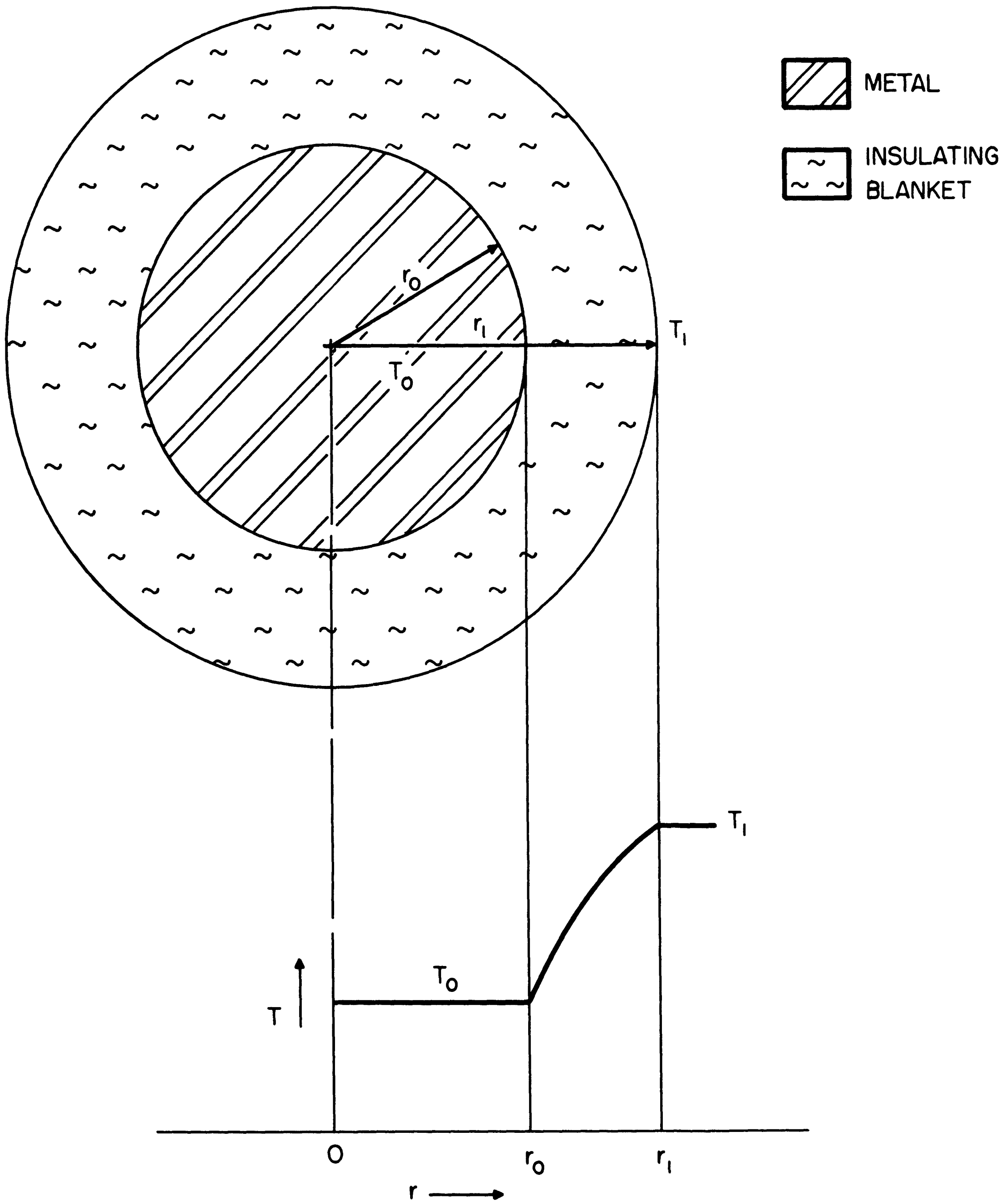


Fig. 10. Temperature distribution in blanket and spherical mass.

Now for a given $\dot{T}_o$, the overall volume occupied by sphere and blanket is minimized when

$$r_1/r_o = 1.5 \quad , \tag{2}$$

and under these conditions, the minimum blanket radius is given by

$$r_1 = 4.5 \sqrt{\frac{K(T_1 - T_o)}{h_v \dot{T}_o}} \quad . \tag{3}$$

Example:

If we now calculate r_1 using readily available materials and assume

$$T_1 - T_o = 70°C$$

$$K = .006 \text{ cal } °C^{-1} \text{ cm}^{-1} \text{ min}^{-1} \quad \text{(Note 1)}$$

$$\dot{T}_o = .01°C \text{ min}^{-1}$$

$$h_v = 0.9 \text{ cal cm}^{-3} \; °C^{-1} \quad \text{(Note 2)},$$

one obtains $r_1 = 30$ cm, or a diameter of about 2 feet! This is obviously an impractical design.

The above analysis however, reveals the rather amazing fact that, if r_o is fixed, the temperature rise rate cannot be made arbitrarily small by merely increasing the size of the blanket. In fact, if we increase the blanket radius r_1 indefinitely, the temperature rise rate [Eq. (1)] cannot be made smaller than 1/3 of the rise rate for the minimum volume condition! This fact has consequences which apply to all methods involving an insulating blanket.

5.4. HEAT OF FUSION

Use is made of the fact that in changing state pure materials absorb and give off heat at the same temperature, regardless of the direction of heat flow. That is, ice melts and partly frozen water freezes at 0°C, with a transfer of $H_f = 80$ calories per gram. Further, the process is not noticeably pressure-sensitive. Material requirements for present purposes are:

(a) Melting point between 35°C and 45°C.
(b) Large heat of fusion, H_f.

Note 1. This is the approximate value for low-density EP-Fome, glass wool or corkboard.

Note 2. A spherical structure containing 90% water by volume. In the example, the water weighs 30 kg.

(c) Large thermal conductivity.
(d) Stable and chemically inactive.

A number of organic and inorganic salts were tested. These all failed to fulfill requirements (c) or (d) or both. Of the metallic elements, there are only three candidates.

Element	Melting Point °C	H_f cal gm^{-1}	Chemical Activity
(a) Cesium	28.5	3.4	oxidizes rapidly in air
(b) Rubidium	38.5	6.1	oxidizes rapidly in air
(c) Gallium	29.75	19.1	stable in air, but readily dissolves metals

A sample of gallium was obtained in an aluminum container protected with a thin film of plastic. However, several melt-freeze cycles sufficed to loosen the protective coating and the gallium dissolved its container. In addition to being expensive ($7.50/gm) and hard to contain, it has an undesirably low melting point.

The next candidate was a eutectic alloy. The only suitable alloy available commercially* is composed of five elements (44.7% Bi, 22.6% Pb, 8.3% Sn, 5.3% Cd, and 19.1% In). It has a melting point of 47°C, a heat of fusion H_f = 3.3 cal gm^{-1}, and does not alloy with an aluminum container. The high density (8.85 gm cm^{-3}) produces a reasonable value of volumetric heat of fusion (29.2 cal cm^{-3}).

An idealized heat of fusion structure is shown in Fig. 11. The oscillator is contained within the spherical case of radius r_c. This is surrounded by a spherical shell of the alloy in a second container of radius r_o, with an enveloping blanket as before.

In the melting mode, heat from the environment at T_1 passes through the blanket and gives a temperature distribution as shown. In this idealized structure no heat can pass into the central case without first encountering a spherical shell of partly molten alloy, the melting taking place at a radius r_b and at the melting temperature T_o. The outer case of the alloy enclosure may be at a slightly higher temperature T_o' due to the gradient in the molten region, r_o to r_b.

In the freezing mode, the temperature distribution is inverted with slight modification. Supercooling may occur in the region between r_b and r_o; however, so long as some solid alloy remains in contact with the inner case r_c, there

*Sold as Cerrolow-117 by Cerro de Pasco Sales Corporation, New York City.

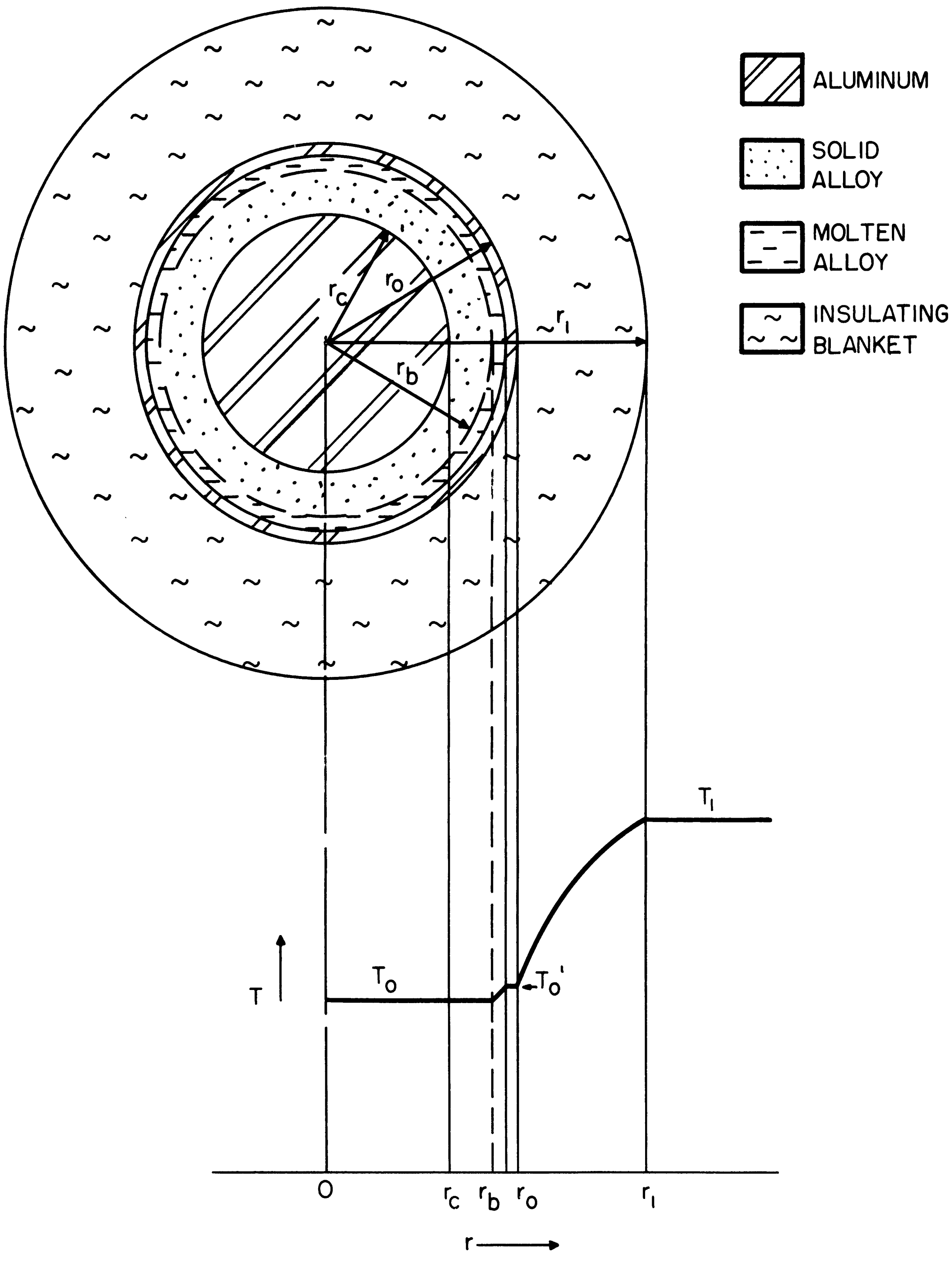


Fig. 11. Idealized heat-of-fusion structure and temperature distribution in melting mode.

will be no supercooling permitted at this interface, and freezing will occur at T_o either at the interface r_b or just inside the shell r_o.

As before, the overall volume occupied by sphere and blanket is minimized when

$$r_1/r_o = 1.5 \quad (2)$$

and we may now calculate the dimension r_1 if a time, t_m, for all the alloy to melt is specified. If x is the fraction of the volume $4/3\ \pi r_o^3$ which is filled with alloy of density ρ, heat of fusion H_f and melting point T_o, the minimum radius of the blanket is*

$$r_1 = 4.5 \sqrt{\frac{t_m K(T_1 - T_o)}{x \rho H_f}}\ , \quad (4)$$

where K is the blanket conductivity, and $T_1 - T_o$ is the temperature differential.

Example:

Let us now calculate r_1 as before, specifying a melting time of 20 minutes

t_m	=	20 min
x	=	0.5 (half the volume is alloy)
$T_1 - T_o$	=	60°C
K	=	.006 cal cm^{-1} $°C^{-1}$ min^{-1}
ρ	=	8.85 gm cm^{-3}
H_f	=	3.3 cal gm^{-1}

Equation 4 gives $r_1 = 3.15$ cm, or an overall diameter of about 2.5 inches. In this case 172 grams of the alloy would be required.

The overall size of a practical design will be somewhat larger; about 200 to 250 grams of alloy will be required.

5.5. PRACTICAL DESIGN OF TEMPERATURE-STABILIZING STRUCTURES

Several designs of a structure suitable for enclosing the beacon oscillator which use the heat-of-fusion principle are currently being investigated. These are tested in an oven (usually at 100°C) as indicated in Fig. 12. To record the temperature, a Type 32A1 thermistor is placed at the measuring point. This is used in a simple bridge circuit feeding a Sanborn recorder. Switches S_1 and S_2

*See Appendix.

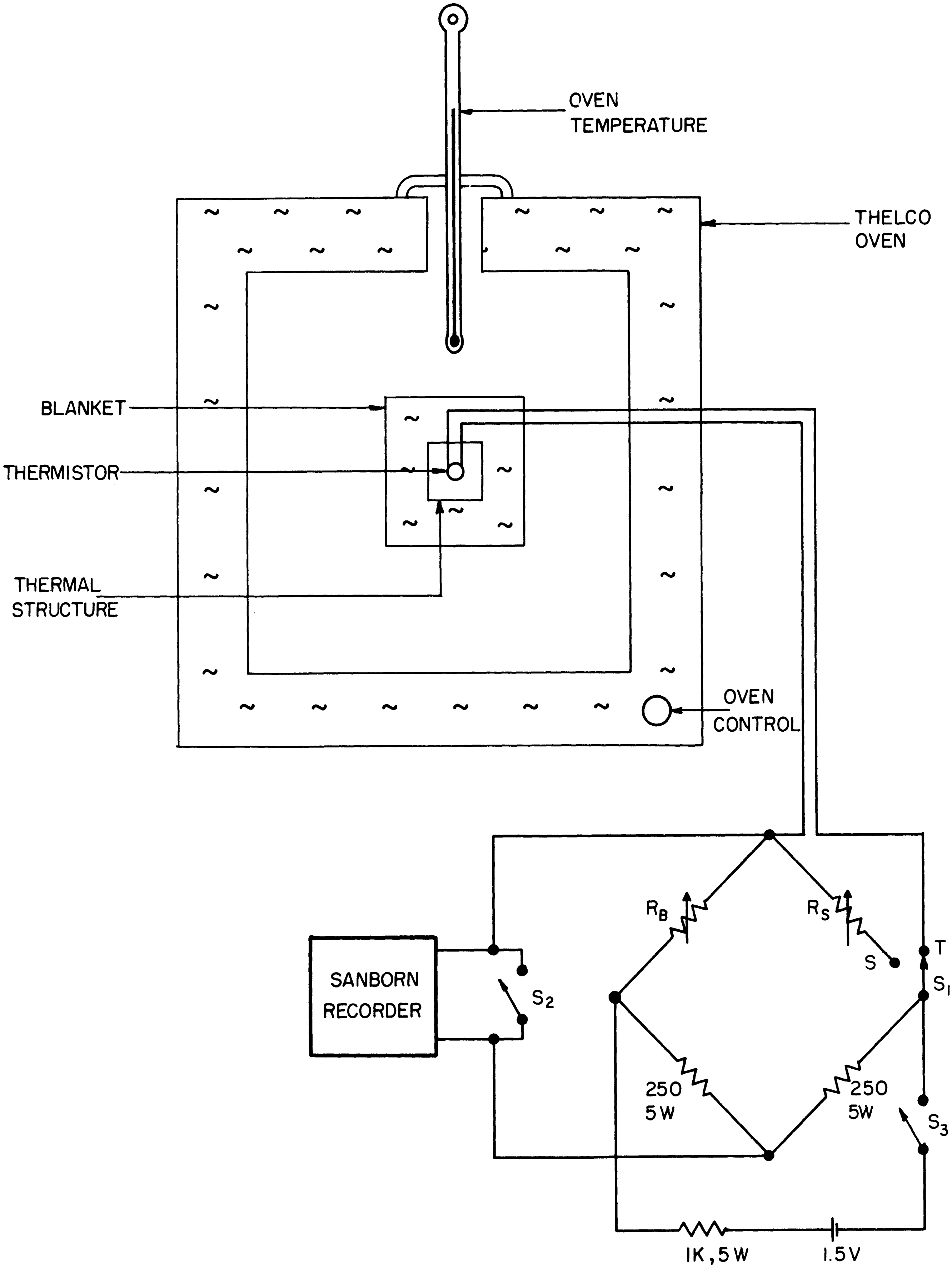


Fig. 12. Set-up for thermal structure tests.

permit temperature calibration of the recorder during a run. The recorder sensitivity permitted a deflection of 1 cm per °C, and the drift error, due largely to the recorder, was about 0.1°C in 15 minutes.

The Cerrolow-117 alloy has been thermally cycled in several containers to check its behavior. Some minor discrepancies have appeared in the re-runs of the melting cycle which are not fully understood at this writing. However, in the freezing cycle the alloy has given satisfactory performance and good repeatability.

Thermal properties of styrofoam and E-P-Fome are currently being studied as blanket materials. Mechanical properties of these materials must also be considered since the completed structure may be required to withstand a thrust acceleration of 160 g's. E-P-Fome of density 8 lb per cu ft has a compressive strength of 150 psi for 10% deflection.* It is expected that this will be adequate.

6. GROUND-STATION EQUIPMENT

The ground-station equipment will be assembled in Ann Arbor of GFE units as soon as these become available. A two-frequency tracking system diagram was prepared for the discussion of December 15, 1958, at BRL. Considerable system revision took place at this meeting, and the frequency ratio of the transmitted frequencies was changed to 4:1. The problem of correcting for nose cone spin and tumble was discussed at some length. It was left with the understanding that BRL would complete the revisions and furnish a new system diagram in the near future.

7. AIRBORNE ANTENNA SYSTEM

Design and testing of the nose-cone antenna system is to be a joint undertaking between BRL and the University since no suitable test facilities are available at our laboratory. Mr. Victor Richard of BRL discussed the design of the 36-Mc antenna with us on December 15, 1958. The actual construction of the antenna system which may be an integral part of the nose cone, will be a joint effort of Tasks 3 and 4.

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*As quoted by the manufacturer, Electronic Plastics Corporation, Brooklyn, N.Y.

APPENDIX

FORMULAE FOR A SPHERICAL HEAT-OF-FUSION STRUCTURE FOR TEMPERATURE CONTROL

Note: Refer to Fig. 11.

<u>Symbols</u>

r_o, r_1	Inner and outer blanket radii (cm)
r_c	Radius of inner case (cm)
x	Fraction of the volume within r_o which is filled with the heat-of-fusion material or alloy
ρ	Density of the alloy (gm cm^{-3})
H_f	Heat of fusion of the alloy (cal gm^{-1})
T_o	Melting point of the alloy (°C)
T_1	Ambient temperature outside the blanket (°C)
K	Thermal conductivity of the blanket (cal min^{-1} $°C^{-1}$ cm^{-1})
t_m	Time required for all of the alloy to melt (min)

Total available fusion heat $= 4/3\ \pi r_o^3\ x\ \rho H_f$ (calories)

Heat input rate through blanket $= 4\pi K(T_1 - T_o)\ r_o\ (1 - r_o/r_1)^{-1}$ (cal min^{-1})

Melting time $$t_m = \frac{x\rho H_f r_o^2 (1 - r_o/r_1)}{3K(T_1 - T_o)}$$ (minutes)

<u>Minimum volume design</u>

Condition for minimum volume of blanket $r_1/r_o = 1.5$

Melting time (min vol) $$t_m' = \frac{x\rho H_f r_o^2}{9K(T_1 - T_o)}$$ (minutes)

Dimensions: $$r_1 = 4.5 \sqrt{\frac{t_m K(T_1 - T_o)}{x\rho H_f}}$$ (cm)

$$r_o = 2/3\ r_1$$

$$r_c = \sqrt[3]{x}\ r_o$$

REFERENCES

1. Craiglow, R. L, and Martin, E. L., "Frequency Control Techniques for Single Sideband," Proc. I.R.E., 44, 1697-1702 (December, 1956).

2. A bismuth-telluride cooling unit of low efficiency, produced by Whirlpool Corporation Research Laboratories, St. Joseph, Michigan, is described in Electronics, 31, 80 (December 5, 1958).