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PHYSIOLOGICAL INSTRUMENTATION
for
FREE RANGING CHIMPANZEES

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Electro-Optical Systems, Inc
A Xerox Company

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6571st Aeromedical Research Laboratory
Aerospace Medical Division
Air Force Systems Command
Holloman Air Force Base, New Mexico

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FOREWORD

This research was conducted from July 1966 to October 1967 in the Biomedical Instrumentation Department of the Measurements System Division, Electro-Optical Systems, Inc., Pasadena, California, under contract No. AF 29(600)-5755, project 6892.

The program was monitored by Mr. Richard F. Chandler, Bio-Effects Division, 6571st Aeromedical Research Laboratory, Holloman AFB, New Mexico.

This technical report has been reviewed and approved.

C.H. KRATOCHVIL, Colonel, USAF, MC
Commander

ABSTRACT

This document is the summation and final report of all work conducted on Air Force Contract Number AF29(600)-6755. All research and development necessary for the fabricating of four chronically implantable instruments is described. The complete instrument comprises conditioning for low level biopotential signals, temperature sensing, two subcarrier oscillators (IRIG Channels No. 9 and 10), a VHF transmitter using FM/FM multiplexing with a range of 1200 feet, a remote switch to activate the instrument and a saturated mercury battery of 500 mAH capacity. The VHF receiving station, including the antenna, was supplied as part of the program. Prime design goals were met such as transmitting range, and IRIG and FCC compatability; the design goal for power consumption was bettered by more than two times to give a powered lifetime of more than 30 days. Total program duration was 15 months.

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SECTION 1

INTRODUCTION

It has been repeatedly demonstrated, over the past decade, that data on physiological response obtained from anaesthetized animals may be erroneous; in the extreme, the evoked response to certain stimuli may be quite wrong. The 6571st Aeromedical Research Laboratory at Holloman Air Force Base is working, with chimpanzees, in the field of comparative physiology. It was desired to gather certain physiological data from these animals when they were located in a normal, social environment.

It has been found that chimpanzees are most aware of any unnatural appendages or attachments to their associates; in fact, any animal so distinguished suffers considerable rough treatment. This physical attack would render useless any attempt to externally telemeter physiological data from such an animal situated with his peers.

The system was intended for usage in the chimpanzee consortium at Holloman Air Force Base and, to ensure reception across the diameter of the enclosure, a 1200 foot range was set as an objective. It was intended that the developed system should be ammenable to additional channels, also that IRIG standards should be followed; though not an inviolate constraint, conformance to applicable FCC specifications was desired.

The original Request for Proposal simply states objectives and general ground rules. The proposed system was an FCC compatible system using FM/FM multiplex of IRIG channels 9 and 10 on a VHF carrier located in the commercial FM band 88 to 108 MHz. Calculations indicated that with best current VHF receiver techniques and suitable receiving antenna, it was possible to achieve the required 1200 foot range without exceeding the FCC limit of 50µV/meter at 50 feet from the transmitter.

Two visits were made to the consortium during the contract. The first to make an rf noise survey and to gain familiarity with the site, and the second to make an on-site evaluation of a prototype prior to freezing of the design of the four refined transmitters.

In the following report the problem is stated as originally proposed by the Air Force and as modified during pre-contract negotiations. This is followed by the Technical Details which form the main body of this report. The division of this section into five sub-sections has been made on a technical rather than a chronological or phase basis; after technical introductory remarks the key problem of signal radiation and reception is examined and analyzed. This is followed by details of the electronic design, then construction of the prototype(s) and finally, the refined transmitters. The report concludes with constructive criticism of what should have been done, what could be done better, and some recommendations for immediate future work in this field.

SECTION 2

SUMMARY

A new telemetry unit, suitable for chronic implantation in small primates, and capable of two channel transmission for up to a quarter mile, has been developed and fabricated on this program. Conducted on contract number AF 29(600)-5755 for the 6571st Aeromedical Research Laboratory, Holloman Air Force Base, an order of magnitude increase in transmitting distance from a chronic implant site has been achieved.

The system developed uses FM/FM multiplexing of IRIG channels 9 and 10 on a vhf carrier for telemetering of biopotential signal and host core temperature. Compatibility with both IRIG telemetry and FCC radiation restrictions was maintained. Transmitter range calculations are presented that indicate the achieved distance is about the maximum that one may expect to obtain within the applicable FCC field strength limit (50 μV/m at 50 feet). A suitable vhf receiver and a specially developed antenna were supplied on the program.

An electromagnetic switch was developed as part of the implant circuitry to allow power to the instrument to be turned ON and OFF from a distance of several feet. Such a switch has not been available in the past and may have general applicability.

As a direct result of work on this program, several new areas of worthwhile study have been delineated and are described at the end of this report. Some of these concern refinements in the telemetry instrument itself, such as coded access to the remote power switch; others could be of more general value, such as a study of antennae suitable for transmission from a physiological site.

The program covered a period of fifteen months; all major technical design goals were met, chief of which were operating life of thirty days and a transmitting range of twelve hundred feet. This new telemetry instrument for chronic implantation should form a useful and sophisticated multichannel tool for physiological research.

SECTION 3
STATEMENT OF THE PROBLEM

3.1 TECHNICAL

It was the purpose of this program to develop a device that was suitable for chronic implanting in small primates (5 to 10 kg chimpanzees); this device was to sense both the core temperature and the electrocardiac potential; it was to multiplex these to a radio frequency carrier, and radiate this composite to a remote receiver. At the receiving location, the two subcarriers were to be demodulated for separate data processing. The primate was to be free to roam in an enclosure of 1200 feet diameter and the ground floor of a building contiguous with the enclosure. The implanted package was to be of such electronic design as to permit the equivalent of at least 30 days continuous operation; it would include a power switch operable to either the ON or OFF position when in proximity (2 to 3 feet) to an excitation unit.

3.2 PHYSIOLOGICAL

An objective of this program was to package the FM/FM multichannel transmitter with a size, shape, and surface finish suitable for chronic implanting in small primates. The duration of implants was planned to be at least twelve months. There was especial challenge to develop an instrument that was small enough to meet the physiological constraints but large enough to transmit an rf signal with good efficiency and to contain sufficient electric battery capacity to yield the desired powered lifetime.

SECTION 4

TECHNICAL DETAILS

4.1 INTRODUCTION

4.1.1 THE CONSORTIUM

The area in which the instrumented chimpanzees will be located is situated at Holloman Air Force Base, New Mexico. It is an area 1200 feet in diameter enclosed by a high (eight foot) chain link fence, the top of which carries insulated wires pulsed with a high electric potential. Some twenty feet inside the fence is a water-filled moat about twenty feet wide, and inside this protective perimeter the chimpanzees are allowed to roam. (It should be noted that the purpose of the fence is as much to keep outside animals outside as it is to keep the chimpanzees inside.)

At the northern edge of the enclosure, a two-story concrete building serves as a feeding and shelter area for the chimpanzees. To enter this building the animals must make their way through a turnstile arrangement; at this point the animals may be held for inspection, ingress and egress to the total structure, or for the purposes of operating a remote electronic switch such as is provided in the transmitting package described herein.

4.1.2 INITIAL CONDITIONS

Within the scope of the original Request for Proposal, particular design decisions were left open. With the acceptance by the Air Force of the approach proposed, initial design decisions were effectively made; the ground rules for the development were defined. The basic initial decisions, together with the various accepted design goals, are presented below.

4.1.2.1 Design Goals

(1) Information Channels: two

(2) Transmission Distance: 1200 feet minimum

(3) Temperature telemetry: 35°C to 41° (inclusive)
±0.1° accuracy

(4) Biopotential (ekg) Telemetry: 0-1 mV
±5% FS nonlinearity
±5% F 2Hz to 100 Hz

(5) Operating Lifetime: 30 days

(6) Remote Power Control: At least two feet range.

(7) FCC Restrictions: Compatible with AFM 100-31, CED 3161.18 Restricted Radiation Devices.

(8) IRIG Standards: Compatible

(9) Movement Artifact: Should be absent from data.

(10) Physical Configuration: Should be such as to permit long-term implant in chimpanzee or large monkey.

4.1.2.2 Initial Decisions

(1) Design Goals: Acceptance of all as design goals.

(2) IRIG Bands: Selection of IRIG channels 9 and 10 for transmission of the temperature and biopotential information respectively.

(3) Battery Capacity: A mercury battery of 1000 mAH capacity was selected as being feasible for powering of the package for 30 days.

(4) Carrier Frequency: Operation in the commercial FM band, viz., 88 to 108 MHz, was selected.

(5) Modulation Method: An FM/FM method was chosen using a modulation index for each of 1.4

(6) Receiver Antenna: Simple crossed dipoles with parasitic reflector located on the roof of the service building.

(7) Receiver: The particular receiver described in the proposal was selected as that to be used, viz., (all units from Vitro Electronics)

Model 1037F Receiver
Model RFT-109-A Tuner
Model FSD 104A Demodulator
Model SSP 101-50-105 Preamplifier
Model PS-102A Power Adapter

4.2 RADIATIVE PATH

The key initial problem requiring examination and decision was that of the transmission path. The information leaves the antenna, passes through living tissue, across the intervening distance, to the receiving antenna. The questions to be answered concern:

(1) radio frequency noise;
(2) radiated power;
(3) transmitting antenna;
(4) receiving antenna.

4.2.1 FREQUENCY SELECTION

A number of considerations entered into the choice of an operating rf frequency, including

(1) Transmitting Antenna Size

A frequency compatible with small antenna size and reasonable radiation efficiency was desirable.

(2) Atmospheric Noise

Since transmitting power was limited by battery weight and space available (as well as by radiation field limitations imposed by the FCC and Armed Services regulations), it was desirable that the limiting signal-to-noise (SNR) factor at the receiver be receiver front-end noise rather than atmospheric noise. (Atmospheric noise considerations become inconsequential above approximately 40 MHz.)

(3) FCC Regulations, Volume II, Part 15 & AFM 100-31,CED3161.18

a. The specifications of CED 3161.18(a)(3), operation above 70 MHZ, did not apply since a duty cycle of one second ON and 30 seconds OFF is specified.

b. Radiation covered by CEC 3161.18(d) did not apply because of the low limit placed on the radiated field (15μV/m, maximum).

c. Allowable limits placed on ISM equipment CED 3161.18 (f) appeared workable but the only operating frequency that was compatible with the GFE receiving equipment (40.68 MHz), was susceptible to both atmospheric noise and sporadic-E layer "skip" interference from other ISM equipment on this frequency.

The higher frequencies (915 MHz, etc.) were not attractive because of problems associated with transmitter design and even greater attenuation by body tissues.

d. The provisions of CED 3161.18(g)(3) allowing limited radiation on any frequency for miscellaneous ISM equipment (effective radiated power of 9.7μW neglecting ground losses) did not appear to apply, since paragraph CED 3161.18 (i)(6), defines miscellaneous ISM equipment as those... "which do not involve communications or the use of radio receiving equipment".

e. The only provision in AFM 100-31 which clearly applied to the problem was that covered in paragraph CED 3161.18 (a)(4).

As a consequence, the system was designed to operate within the 88 to 108 MHz band and to comply with those applicable field strength restrictions.

4.2.2 DC INPUT POWER TO FINAL

Calculation of allowable Effective Radiated Power (ERP)

For Free Space

$$P = \frac{P_t}{4\pi R^2} = \frac{E^2}{120\pi}$$

where: P = power density (watts/meter^2)

P_t = ERP(watts)

R = distance from transmitting antenna (meters)

E = Field strength at distance R from transmitting antenna (volts/meter)

Rearranging: $$P_t = \frac{E^2R^2}{30}$$

$$E = \frac{\sqrt{30\ P_t}}{R}$$

Under the provisions of AFM 100-31, "Electromagnetic Compatibility and Frequency Management" the field strength limit of 50μV/meter in the 88 to 108 MHz band applies at 50 feet or greater from the transmitter.

$$E_{max} = 50\mu\text{V/meter (at 50 feet, 15.3 meters)}$$

$$P_t = \frac{[50 \times 10^{-6}]^2 \times [15.3]^2}{30}$$

$$= 2 \times 10^{-8}\ \text{watt}$$

$$= 0.02\ \text{watt or } -77\ \text{dBW}$$

This level represents the maximum allowable effective radiated power from the transmitting antenna.

In order to arrive at the dc power level input to the rf transmitter the following assumptions were made:

Antenna efficiency	-30 dB
Transmitter efficiency	-10 dB
Transmission loss through body tissue*	-10 dB
Total Losses	50 dB

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*Technical Documentary Report No. SAM-TDR-63-36, USAF School of Aerospace Medicine, Brooks AF Base, Texas, Baldwin, H.A., Development of Telemetry Devices for Dental Research.

Maximum allowable power input to the transmitter, Q, is given by

$$\begin{aligned} Q &= \text{ERP} + \text{losses} \\ &= -77 + 50 = -27\text{dBW} \\ &= 2 \text{ mW} \end{aligned}$$

4.2.3 RANGE CALCULATION

Subject to various regulatory constraints (FCC) the maximum power that may be radiated for this application has been calculated. Within the current state-of-the-art, what then is the maximum distance at which a useful signal may be received? This is calculated in the manner shown below.

$$\begin{matrix}\text{Maximum} \\ \text{ERP}\end{matrix} - \begin{matrix}\text{Free Space} \\ \text{Attenuation}\end{matrix} = \begin{matrix}\text{Receiver} \\ \text{Noise}\end{matrix} + \begin{matrix}\text{Margin for} \\ \text{Necessary SNR}\end{matrix}$$

a. Maximum ERP.....previously calculated to be -77 dBW

b. Free Space Attenuation, α is given by

$$\alpha = \left(\frac{\lambda}{4\pi R}\right)^2$$

where λ wavelength meters (3 for 100 MHz)

R is the range to be determined, meters

c. Receiver noise, P_n, is given by

$$P_n = KTB$$

where K is Boltzmann's Constant 1.38×10^{-23} joules/°K

T is the absolute temperature, 310°K

B is receiver bandwidth, 50 KHz

Substituting these values give:

$$P_n = 1.38 \times 10^{-23} \times 310 \times 5 \times 10^4$$
$$= 2.14 \times 10^{-16} \text{ Watt}$$
$$= -156.7 \text{ dBW}$$

d. Margin for Necessary SNR...12 dB is approaching a workable minimum and is used in this calculation.

The signal level required at the antenna for satisfactory operations must be greater than the receiver front end noise power by the inherent receiver noise, given as 4.5 dB, together with a margin to give the necessary SNR (12 dB).

Thus the signal level required at the antenna

$$= -156.7 + 4.5 + 12$$
$$= -140.2 \text{ dBW}$$

Since the effective radiated power is at -77 dBW the maximum loss that may be sustained due to free space attenuation is

$$-77 - (-140.2) = 63.2 \text{ dB}$$

In the process of radiating electromagnetic energy at about 100 MHz over the dry terrain of New Mexico a ground loss will be sustained for which 3 dB represents a reasonable estimate.

The allowable loss in transit must therefore be reduced by a further 3 dB to 60.2 dB.

So: **Free Space Attenuation at Maximum Range** = 60.2 dB

$$\left(\frac{\lambda}{4\pi R}\right)^2 = 10^{-6} \quad \text{(restoring the ratio)}$$

$$\frac{\lambda}{4\pi R} = 10^{-3}$$

i.e., $$R = \frac{3}{4\pi} \times 10^3 \text{ meters}$$
$$= 238 \text{ meters} = 780 \text{ feet.}$$

The receiving antenna to this point has been assumed to have no forward gain, however since the antenna is to be positioned at one side of the enclosure, parasitic reflector elements may be used to raise the forward gain by at least 3 dB. This antenna gain increases the allowable path loss to 63.2 dB

63.2 dB corresponds to a ratio of 4.8×10^{-7}

$$R = \frac{\lambda}{4\pi\,(4.8 \times 10^{-7})^{\frac{1}{2}}} = \frac{3 \times 10^{4}}{4\pi\sqrt{48}} = 346 \text{ meters}$$

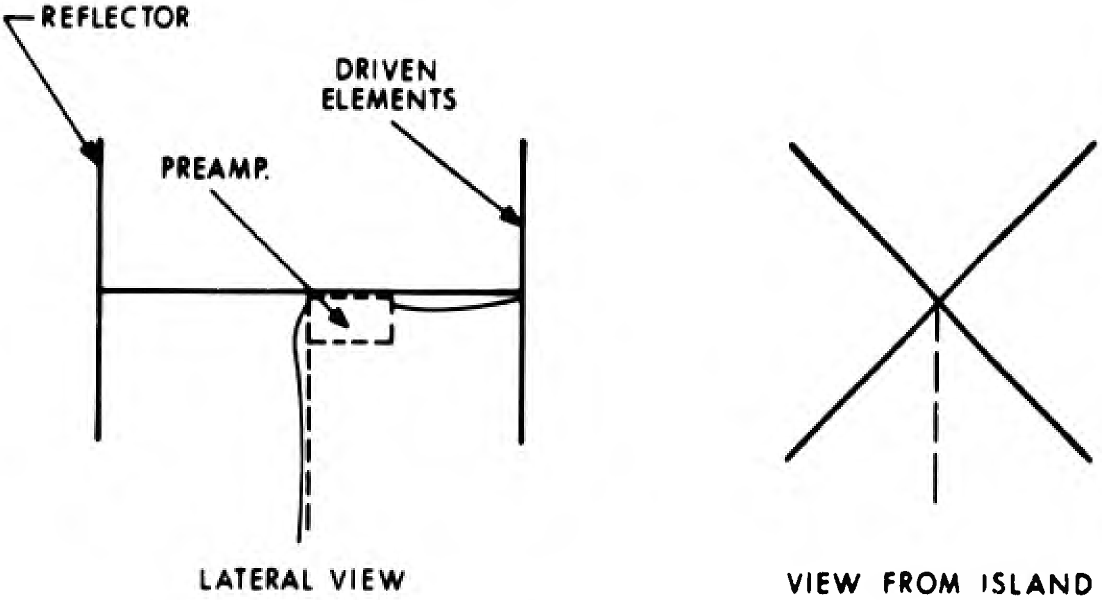
$$= 1140 \text{ feet}$$

We may expect a limit of transmission in the region of 1200 feet.

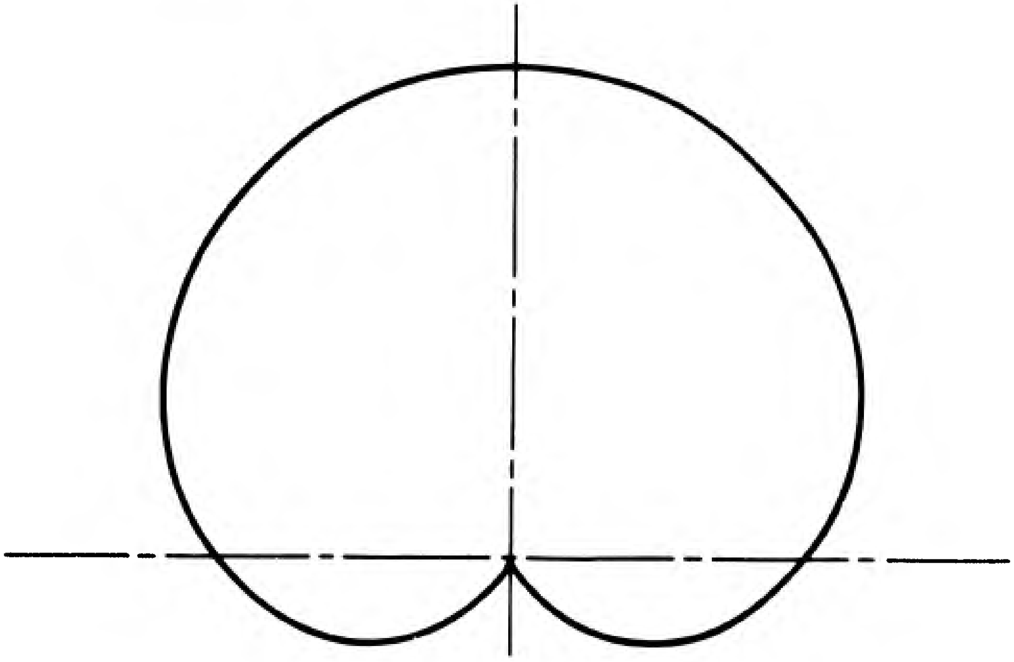
4.2.4 THE RECEIVING ANTENNA

The service building was selected as the site for the receiving antenna. The antenna was to be made up of two half-wave dipoles fixed at right angles to each other, fed 90 degrees out of phase, and with a parasitic reflector (Figure 1-a). As noted in the previous calculation an approximate gain of +3 dB is realized over an isotropic radiator. This antenna configuration was chosen because of its relative insensitivity to the polarization of received waves. The reflector provides most of the forward gain, with attendant attenuation of signals arriving from the rear 180 degree sector (Figure 1-b). Additional forward gain (more parasitic elements) is not deirable because of the resulting decrease in beamwidth.

Use of the perimeter fence as a receiving antenna was considered at an early stage of the program. It was eliminated since many problems were anticipated in its utilization, whilst neither theoretical nor practical problems were discovered with application of the crossed dipoles.



(a) MECHANICAL CONFIGURATION



(b) TYPICAL RESULTANT ANTENNA PATTERN
(BOTH VERTICAL AND HORIZONTAL PLANES)

Figure 1. The Receiving Antenna as Proposed

The type of receiving antenna selected was set up in the Sherman Oaks area of Los Angeles. The mechanical arrangement was such as to permit adjustment of interelement spacing as well as individual lengths of all elements, both driven and passive (Figure 2). During each pattern test a particular commercial FM station was chosen as source and the relative incident field strength recorded as the antenna was remotely rotated.

A particular set of dimensions was chosen as follows:

Driven element overall length	62 inches	0.47λ
Parasitic reflector length	66 inches	0.50λ
Inter-element spacing	32 inches	0.244λ
Nominal resonant frequency	90 MHz	

This arrangement gave a maximum total variation of 3 dB in sensitivity to a plane polarized incident wave, (Figure 3). In comparison to a reference antenna of simple crossed dipoles with no reflector, a minimum enhancement in forward gain of about 4 dB was obtained. The enhanced forward sensitivity was maintained over a 170° arc (Figure 4). The two driven dipoles were coupled through a suitable phasing stub and then fed to the mast mounted preamplifier by a transmission line balun. This antenna, of gold anodized aluminum, with the preamplifier, is shown in Figure 5.

4.2.5 THE VHF RECEIVER

(1) Receiving Preamplifier

A preamplifier following the receiving antenna is necessary in order to improve the receiving system noise figure. (The receiver, Vitro Type 1037A, has a noise figure of 6 dB.)

(2) Preamplifier Characteristics

Type	Vitro Mod. SSP-101-50-105
Noise Figure	4 dB
Gain	25 dB minimum
Bandwidth	55 MHz (50 to 105 MHz)

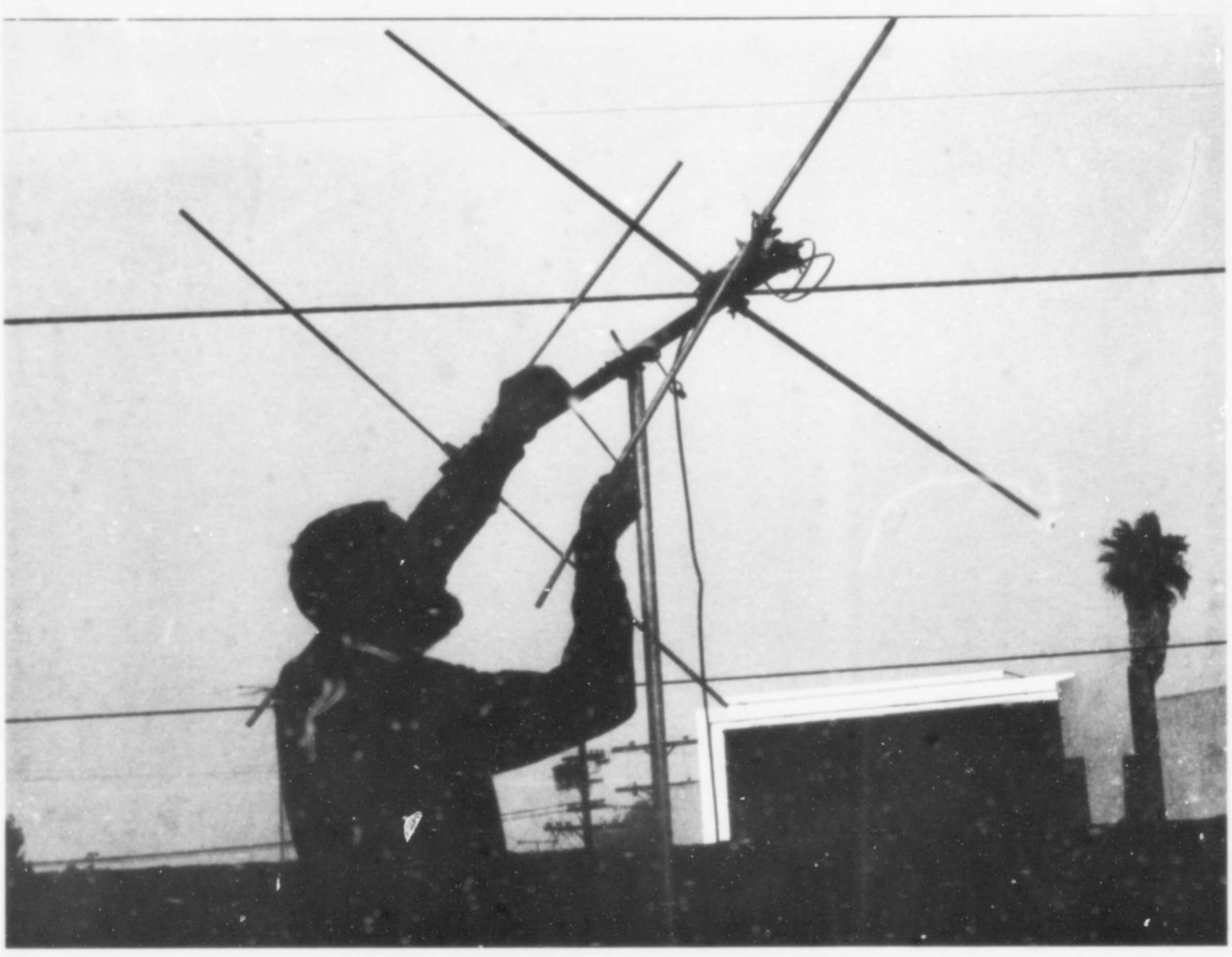


Figure 2. Adjusting the Length on One of the Driven Elements of the Receiving Antenna

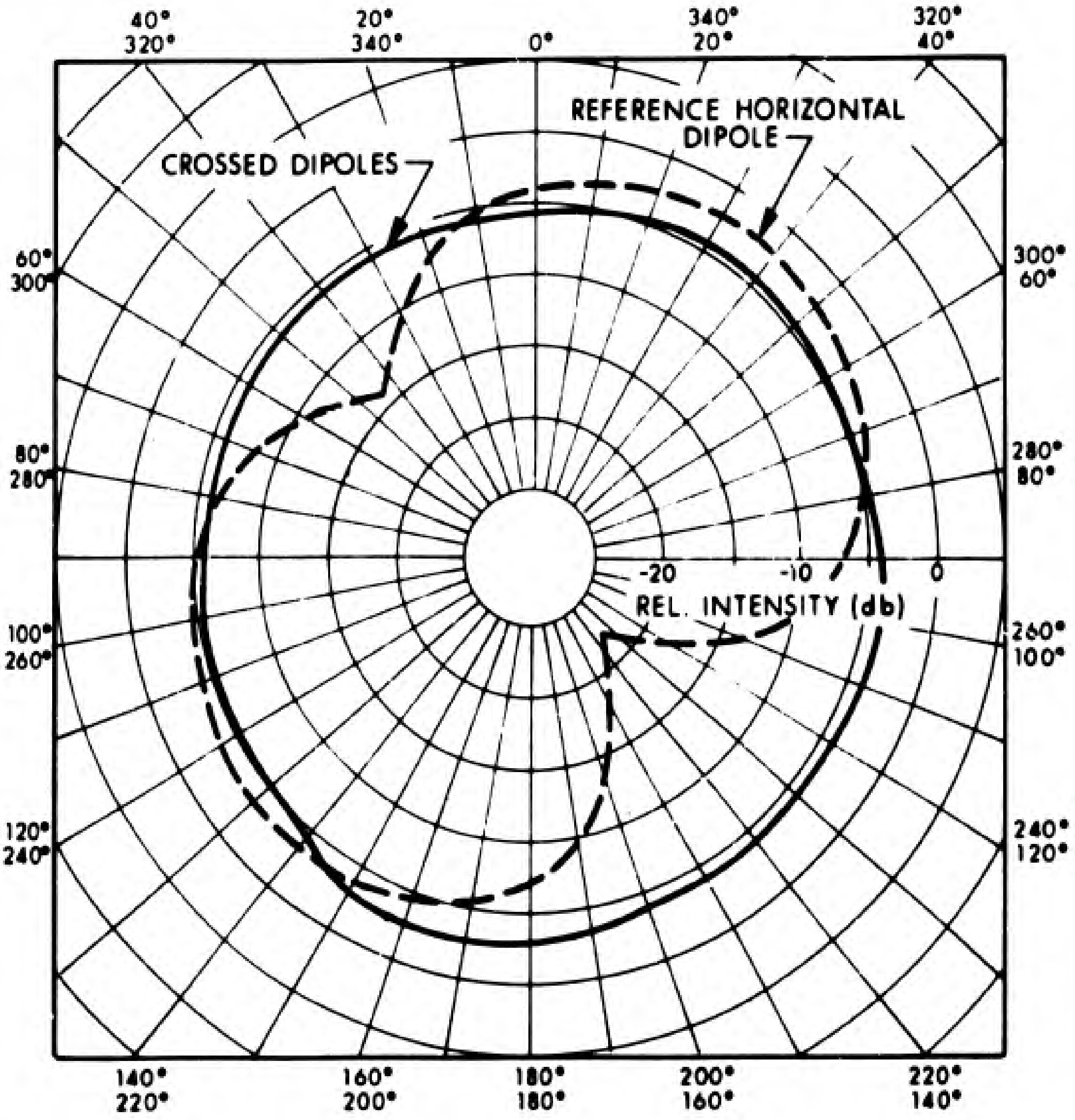


Figure 3. Receiving Antenna Field Intensity Pattern; Crossed Dipoles Referenced to a Horizontal Dipole, $f_c = 90$ MHz.

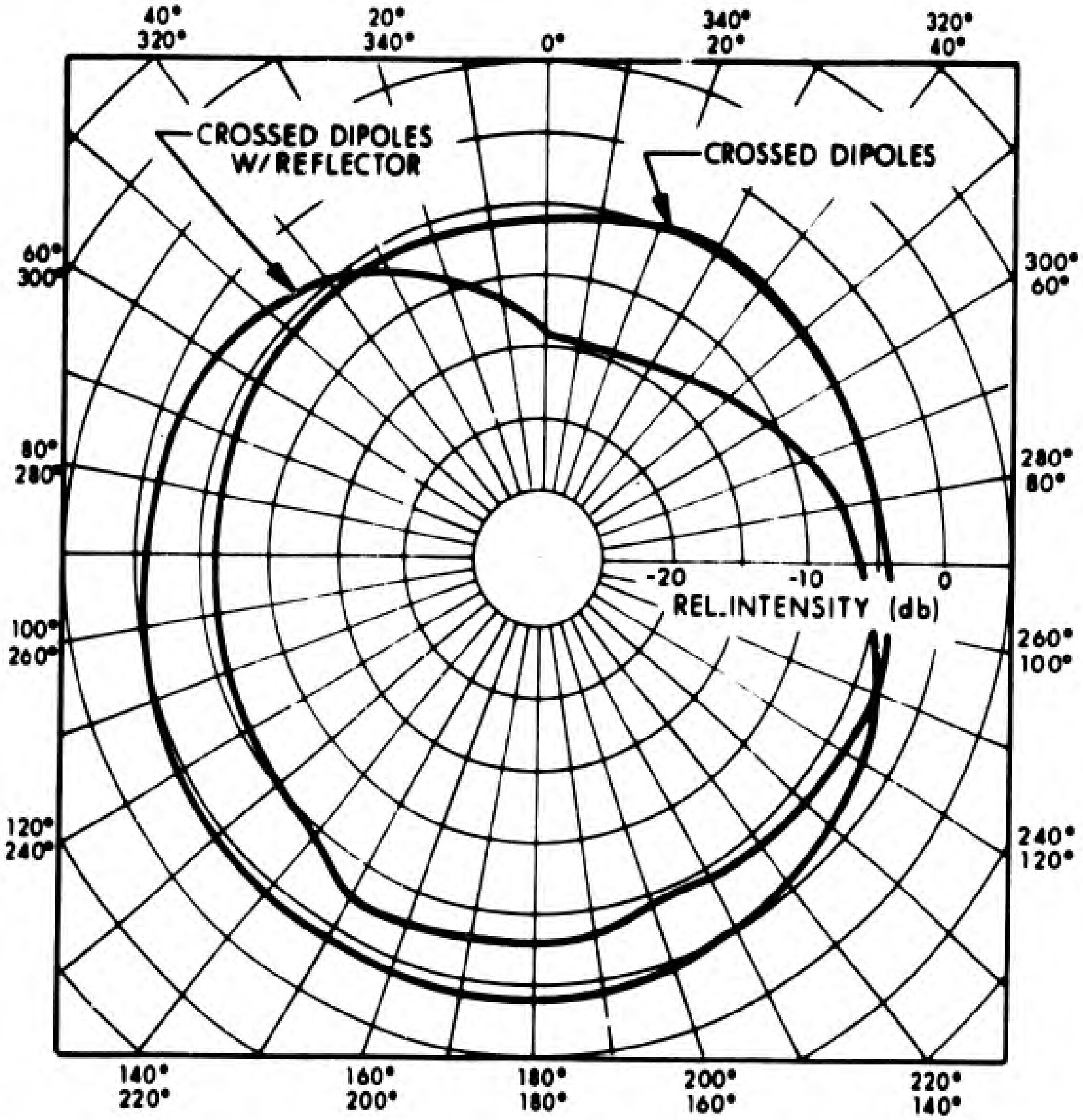


Figure 4. Receiving Antenna Field Intensity Pattern; Crossed Dipoles with and without Reflector - f_c = 90 MHz.

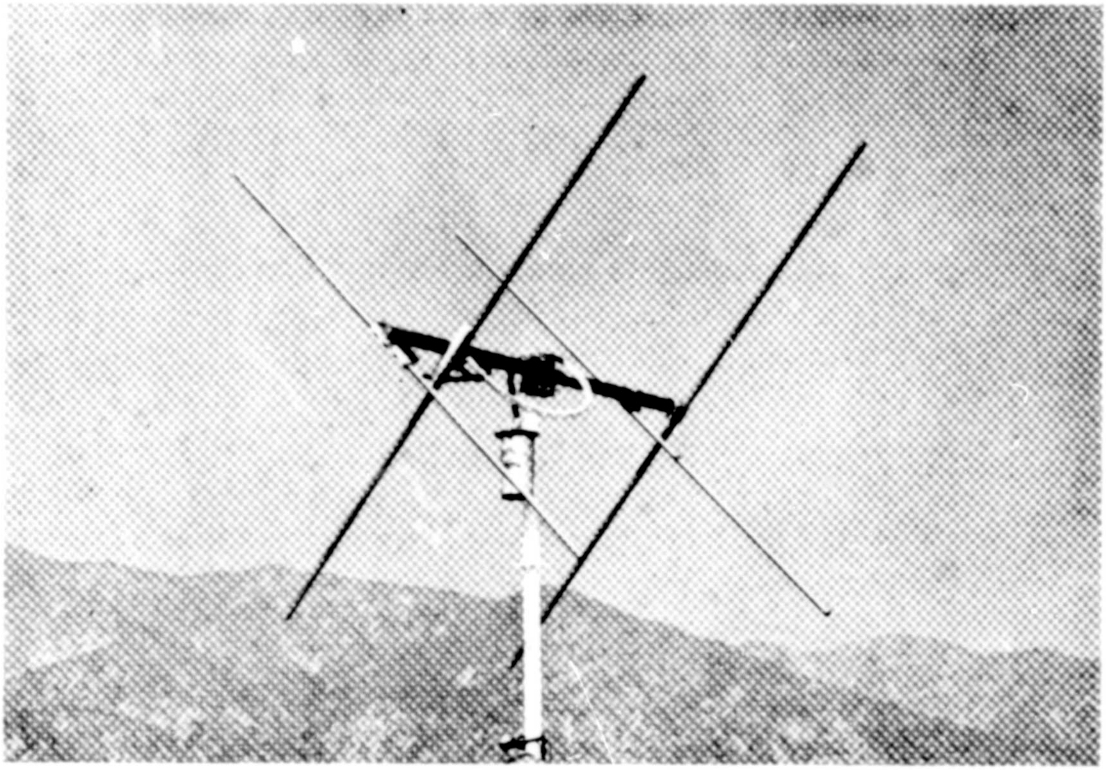


Figure 5. The Completed Receiving Antenna. (The transmission line balun may be seen. The cable to the receiver is not connected in this photograph.)

Use of this preamplifier reduces the system noise figure to slightly over 4.0 dB. (4.5 dB used in range calculations.)

(3) **Receiver**

The receiver chosen for this system is the Vitro Model 1037A with a 50 kHz i.f. module installed. Use of alternate receivers such as the type 1670 or 1503 (i.f. bandwidth 300 kHz) was not recommended due to the narrow system margin of SNR.

As discussed in subsection 4.1.2.2, two FM subcarriers are employed, operating at 3.9 kHz and 5.4 kHz. The rf modulation indices, $M_{3.9}$ and $M_{5.4}$ were each chosen to be 1.4, thus the basic i.f. bandwidth is dictated by the second order side current pair generated by the 5.4 kHz oscillator. This set a minimum i.f. bandwidth of approximately 15 kHz. In order to allow for transmitter drift and detuning tolerance, the i.f. bandwidth was increased to 50 KHz. This permits a variation of the r f center frequency to approximately ±17 kHz.

(4) **Receiver Characteristics**

Type	Vitro Model 1037A
i.f. bandwidth	50 kHz
Tuning range	55 to 260MHz
Noise figure	6 dB
Detector type	Foster-Seely

4.3 ELECTRONIC CIRCUIT DETAILS

The proposed system utilizes frequency division for multiplexing the two channels of biophysical data on the rf carrier. Two fm oscillators on IRIG bands 9 and 10 are employed.

Temperature data, essentially steady state modulates the channel 9 (3.9 kHz) oscillator; the range of 35°C to 41°C was set to correspond with a ±7.5 percent deviation of the subcarrier frequency from center. In order to maintain IRIG compatibility, the lowest available IRIG cutoff frequency (6Hz) should be used for the receiving system discriminator low pass filter.

EKG data, carrying frequency components up to approximately 100 Hz, modulates the channel 10 (5.4 kHz) oscillator. Deviation sensitivity is such that a peak-to-peak signal of 1 mV will result in approximately 1/3 of subcarrier bandwidth (±7½%) deviation. This permits toleration of a certain amount of artifact movement and oscillator drift. The IRIG filter used at the channel 10 discriminator output should have a 110 Hz cutoff frequency.

The outputs of the two oscillators are linearly mixed and applied to the transmitter modulation input. The oscillator output amplitudes are adjusted to result in identical rf modulation indices of $M_{3.9} = M_{5.4} = 1.4$.

A signal conditioner is required to amplify the ekg signal prior to its modulating the voltage controlled oscillator.

The battery power to the chronically implanted package must be switchable OFF or ON by some device external to the body of the host. To accomplish this switching function, some form of energy must be transmitted to the implant and suitably processed.

Several subcircuit developments were necessary as indicated by the above text. Each of these is described in this section in the following order:

(1) Battery capacity - system constraints.
(2) Voltage controlled oscillators.
(3) Amplifier, band pass and mixing

(4) Biopotential amplifier,

(5) Remote switch,

(6) VHF oscillator and antenna feed.

4.3.1 BATTERY CAPACITY - SYSTEM CONSTRAINTS

In order to define the required battery power source it was necessary to make an estimate of the total power demand. In Table I the assessment of current drains originally presented in the proposal are given. The current drain estimates proved to be conservative. They are noted at this point since it is necessary to decide how great a battery capacity is required and also to apportion the power for the setting of individual design goals.

TABLE I

CIRCUIT FUNCTION	PROJECTED CURRENT DRAIN	
Transmitter Final*	330 μA	
Oscillator	200 μA	
Subcarrier VCO-1	300 μA	
Subcarrier VCO-2	300 μA	
Signal Conditioning	100 μA	
Proximity Switch ON	70 μA	
Proximity Switch OFF		10 μA
TOTAL ON CURRENT	1300 μA	
TOTAL OFF CURRENT		10 μA

If a ratio of OFF/ON time of ten to one is assumed, the following battery capacity may be calculated:

ON work, 720 hours at 1300 μA	935 mAH
OFF work, 7200 hours at 10 μA	72 mAH
Battery capacity needed	1007 mAH

---

*This figure assumed a supply potential of 6 Vdc and used the 2mW power limit calculated in Subsection 4.2.2.

Mercury cells were selected for this application because of their great relative capacity and their inherent absence of leakage. Silver cells do have a slightly greater work storage since the cell voltage is a little greater and their ampere-hour/unit volume is about the same as the mercury cell. The mercury cell, however, is routinely available in much greater capacities (larger cell sizes) than the silver, and higher quantity production techniques have made high-reliability versions available.

In Table II a group of 500 and 1000 mAH mercury cells are grouped to show some of the sizes, capacities and battery voltages available.

TABLE II

Designation	Voltage	Capacity (mAH)	Dimensions	Weight (oz)	No. Reqd. 1000 mAH	Connection
E132	2.70	1000	1.3 x 0.66D	0.9	2	series
E163	4.20	500	1.3 x 0.66D	0.87	2	parallel
E133	4.20	1000	1.95x 0.66D	1.4	1	-
E164	5.60	500	1.75x 0.66D	1.16	2	parallel
E134	5.40	1000	2.6 x 0.66D	1.9	1	-
E165	7.00	500	2.2 x 0.66D	1.45	2	parallel

It was desirable to operate the system all at one voltage for simplicity and it was also advantageous to use the lowest practical potential in order to maximize available ampere hours. Since battery volume bears a roughly direct relationship to capacity or watt-hours,

i.e.: Volume & Weight α Watt-hours = V.I.T.

Where V is the battery potential

I is the fixed current drain

T is the time for the potential to fall a given amount.

Since transistors are current operated devices it was desirable to keep the available current as great as possible; it will be seen in the relationship above that if total time, T, and battery size are fixed, then to maximize available current drain, I, the potential, V, should be minimized, i.e., held to as low a value as possible without compounding such problems as stability due to temperature coefficients of V_{BE} and so forth. The battery potential initially selected was 5.4 Vdc, that available from a stabilized mercury battery of four cells.

4.3.2 VOLTAGE CONTROLLED OSCILLATORS (VCO)

The basic approach to this low power design was rather straight-forward. No special techniques were found to be necessary. The restricted range of temperature in biomedical applications is a material assistance in this regard - temperatures are not so high that reverse leakage current is troublesome or so low that forward current gain drops substantially.

It was rapidly ascertained that the simple VCO shown in Figure 6 would perform quite well. At first glance, one would expect that changes in the V_{BE} turn on potential ($2mV/^{o}C$) would cause substantial frequency shift, especially at low supply voltages where V_{BE} would represent a significant proportion of the supply voltage. These fears proved to be groundless and the reason is set out below.

As each transistor switches ON, there will be transferred to the base of the transistor that <u>was</u> ON, a negative voltage step of $E_{cc} - V_{CE(sat)}$, i.e. the voltage drop that occurs at the collector of the side going ON. This voltage will exist with respect to the voltage previously present on the base lead, i.e., $V_{BE(ON)}$, so that the maximum negative value momentarily reached at the base of the OFF transistor is given by

$$-(E_{cc} + V_{CE(sat)}) - V_{BE(ON)} = -E_{cc} - V_{CE(sat)} - V_{BE(ON)}$$

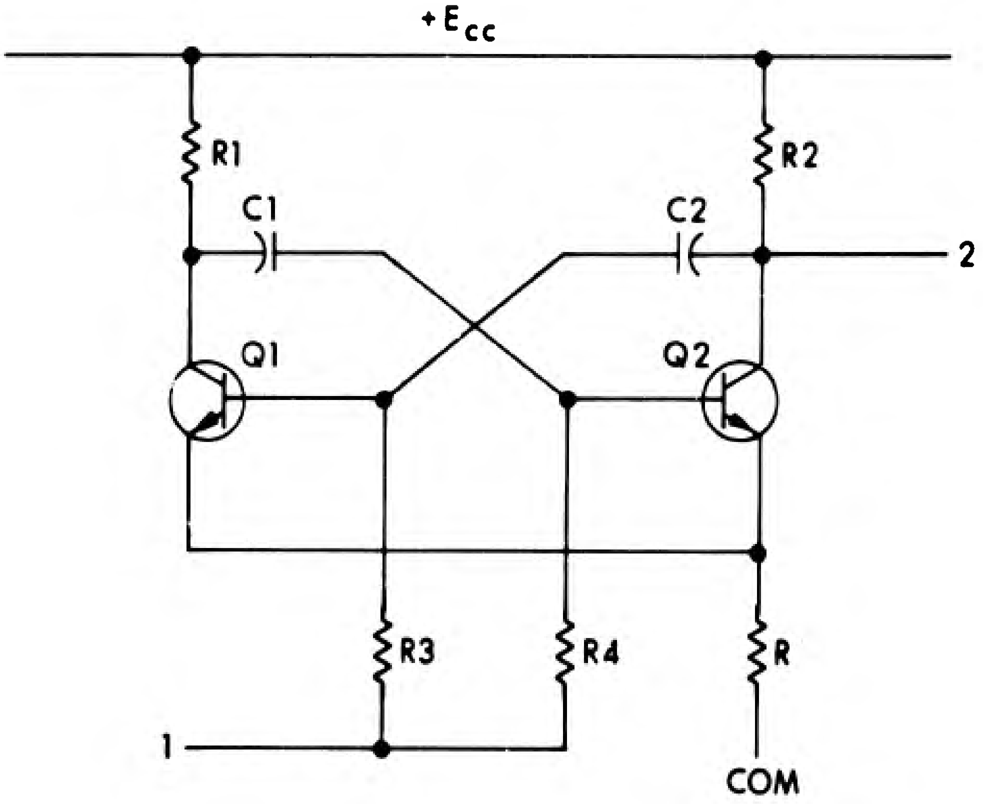


Figure 6. The Basic Voltage Controlled Oscillator

The transistor will switch again when this base voltage recovers to approximately $V_{BE(ON)}$. The difference between the most negative potential and that required to turn the stage ON is given by

$$-E_{cc} - V_{CE(sat)} - V_{BE(ON)} + V_{BE(ON)}$$

$$\text{i.e.} \quad E_{cc} - V_{CE(sat)}$$

This voltage, through which the base will swing, sets the half cycle time of the oscillator. If it is constant then the frequency will be essentially constant.

The first VCO built up had a current drain of 120 μA from 5.4 volts (650 μW). This current was reduced in two steps to approximately 30 μA (160 μW); it is expected that the current could have been further reduced except that problems were experienced in maintaining reasonable collector waveforms. With the final values used the time constant of the collector was approximately half that of the biasing or charging network; a relationship of this nature tends to produce frequency instabilities or jitter, however, none was experienced.

T final circuits used for channels 9 and 10 are shown in Figures 7 and 8 respectively. Each is followed by a band pass amplifier which is described in the following subsection.

Temperature test of a channel 10 subcarrier oscillator, at fixed input bias, over a temperature range from 26°C to 43.4°C, showed a frequency increase of 50 Hz.

Thus:
$$\text{Temperature Coefficient of frequency} = \frac{50}{17.4} \times \frac{100}{5400} = 0.053\%/^{\circ}\text{C}.$$

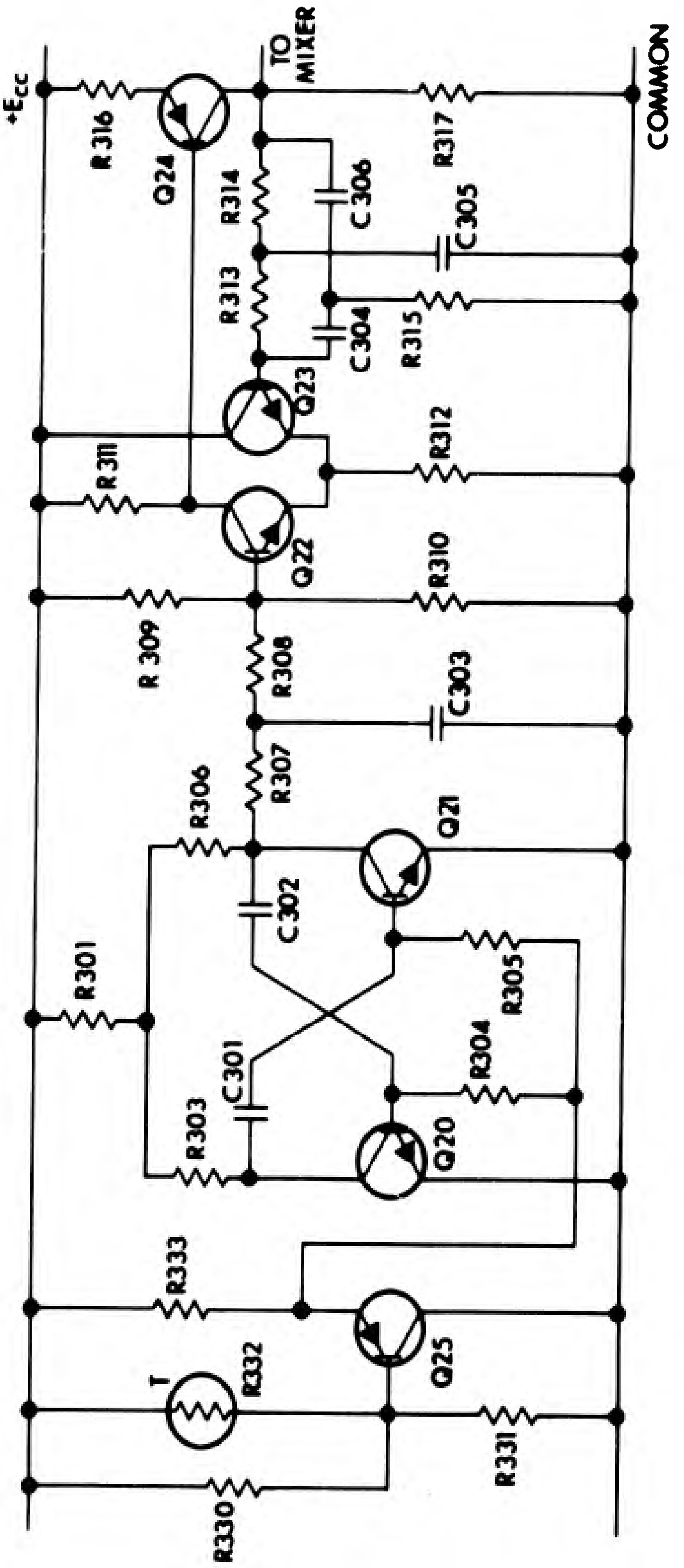


Figure 7. The Temperature Measurement Channel, IRIG Number 9, 3.9 KHz.

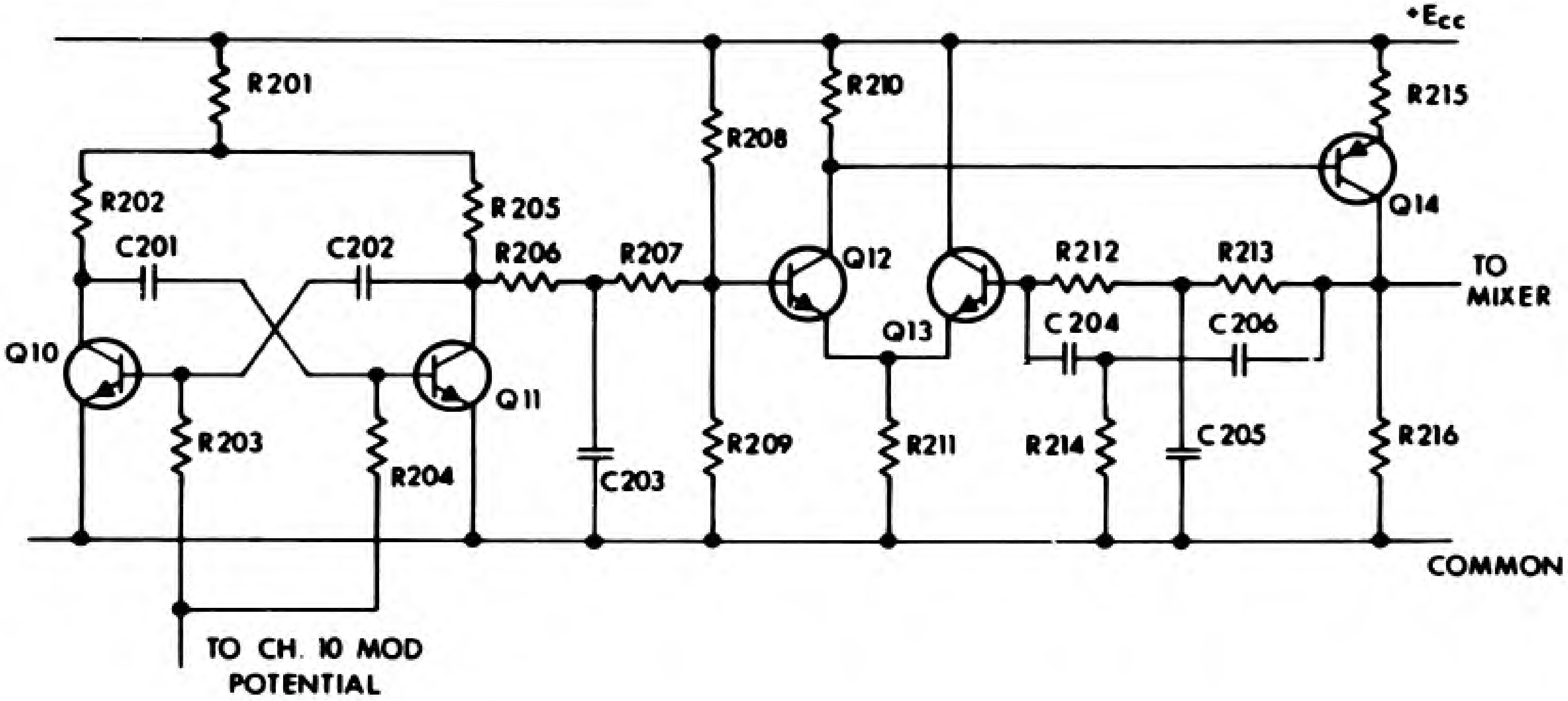


Figure 8. The Biopotential Channel, IRIG Number 10, 5.4 KHz.

The method of modulating the channel 9 VCO with temperature data is shown in Figure 8. A thermistor, R332, conducts current from the main supply rail to the base of the transistor, Q25. The impedance at this base point is essentially set by the parallel combination of R330 and R331. The thermistor used was a VECO type 65A6 bead. The salient characteristics of the calculation are as follows:

TEMPERATURE	THERMISTOR RESISTANCE	BIAS LEVEL TO VCO	VCO FREQUENCY
35°C	2.95M	2.26 Vdc	3.750 kHz
40°C	2.25	2.45 Vdc	4.050 kHz

The VCO draws an approximately constant base drive current of 9 µA. That it was necessary to add the emitter follower may be shown as follows (assuming the use of this particular thermistor).

If the thermistor is connected directly from the supply potential of 5.4 Vdc to the VCO drive, then

Current through thermistor at 35°C $= \dfrac{5.4 - 2.26}{2.95} = 1.07$ µA.

Current through thermistor at 40°C $= \dfrac{5.4 - 2.45}{2.25} = 1.31$ µA.

a change in current of 0.24 µA,

The required change in potential at the VCO input is

$2.45 - 2.26 = 0.19$ Vdc.

Therefore effective sink impedance for thermistor must be

$$\frac{0.19\text{V}}{0.24\mu\text{A}} = 0.79\ \text{M}\Omega$$

But the VCO represents an impedance approximating

$$\frac{2.3\text{V}}{9\mu\text{A}} = 0.26\ \text{M}\Omega$$

An emitter follower is therefore required.

The purpose of this emitter follower is to present a satisfactory load to the thermistor and supply the needed drive current (approximately 9μA) to the VCO. Straightforward calculations revealed that R330 and R331 should be chosen to give a parallel value of about 0.61 MΩ and must also be chosen in each case to set the potential to the channel 9 VCO such as to give the desired output frequency at the particular setup temperature.

The temperature test of a channel 9 subcarrier oscillator and thermistor driver, over a temperature range from 31.5°C to 43.4°C, gave a sensitivity of 0.92%/°C, corresponding to approximately 36 Hz frequency increase for each 1°C increase.

4.3.3 AMPLIFIER, BAND PASS AND MIXING

Although never ultimately realized within this program, it was the intention that various of these circuits would be built up using thick-film techniques. A direct result of that original intent was the making of this simple amplifier circuit (Figure 9); this one subcircuit was thought to be most compatible with its being built up on a chip and various external components simply added to it to set function.

The waveform at the output of the multivibrator VCO is an approximate square wave and suppression of most harmonics is necessary. It is also required that these two sine waves be summed (linearly mixed) for modulation of the rf oscillator. This single amplifier is used to perform both these functions (Figure 10); as a summer it was intended to direct couple the output to the rf oscillator. When this scheme was tried it was immediately clear that there was substantial dc gain from the reference input to the output. Since it was essential that this dc level to the oscillator be held constant, a capacitively coupled emitter follower was added, after the mixing function to drive the vhf oscillator (Figure 11).

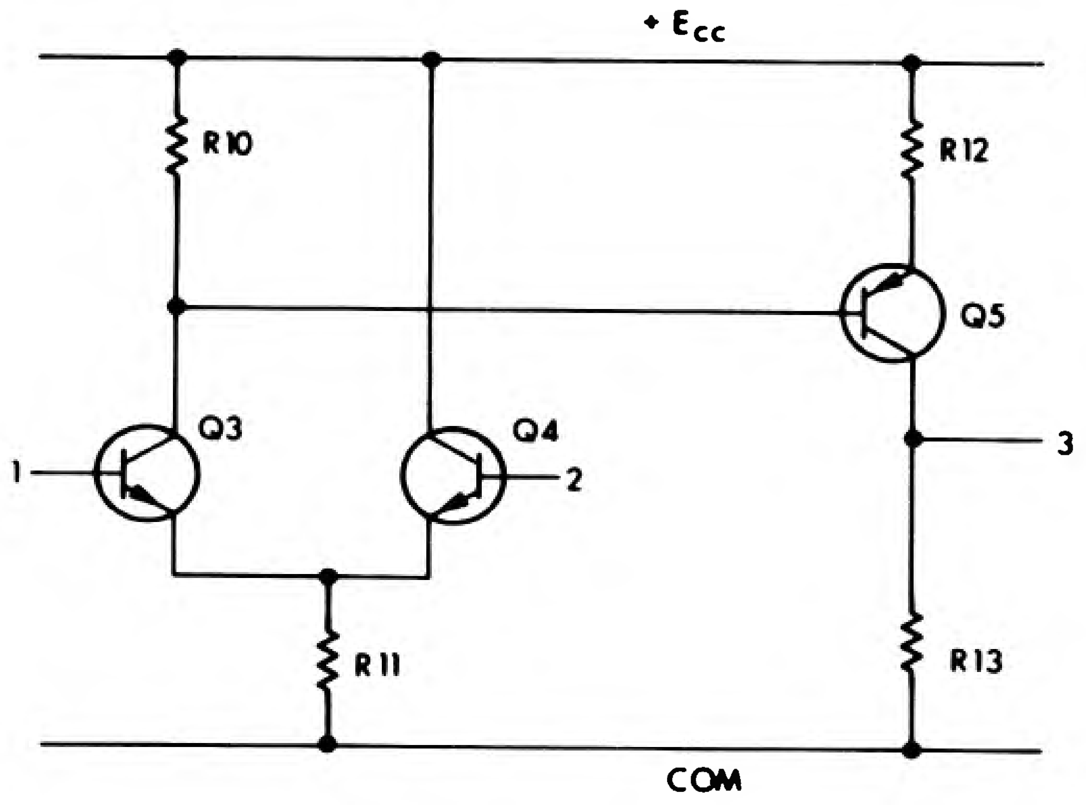
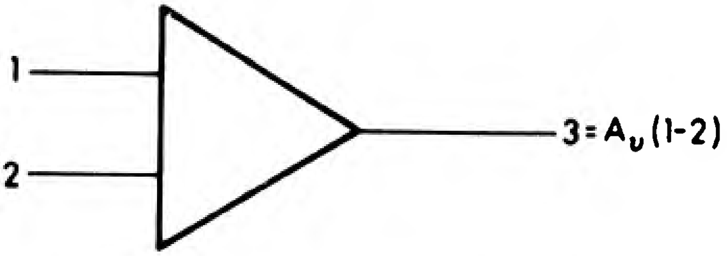
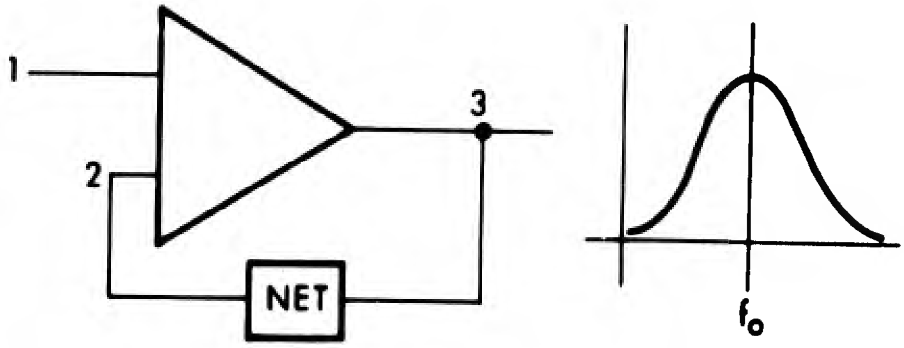


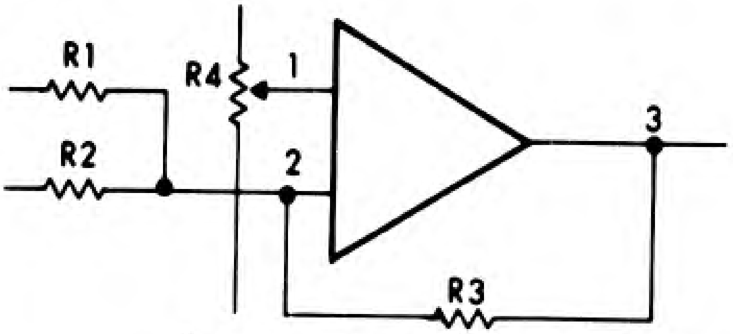
Figure 9. The General Purpose Amplifier -- Power Consumption was 50 μW.



(a) THE AMPLIFIER BLOCK



(b) AS A BAND PASS AMPLIFIER
NET: FREQUENCY STOP NETWORK,
(e.g. twin-T)



(c) AS A SUMMING AMPLIFIER

Figure 10. Applications of The General Purpose Amplifier.

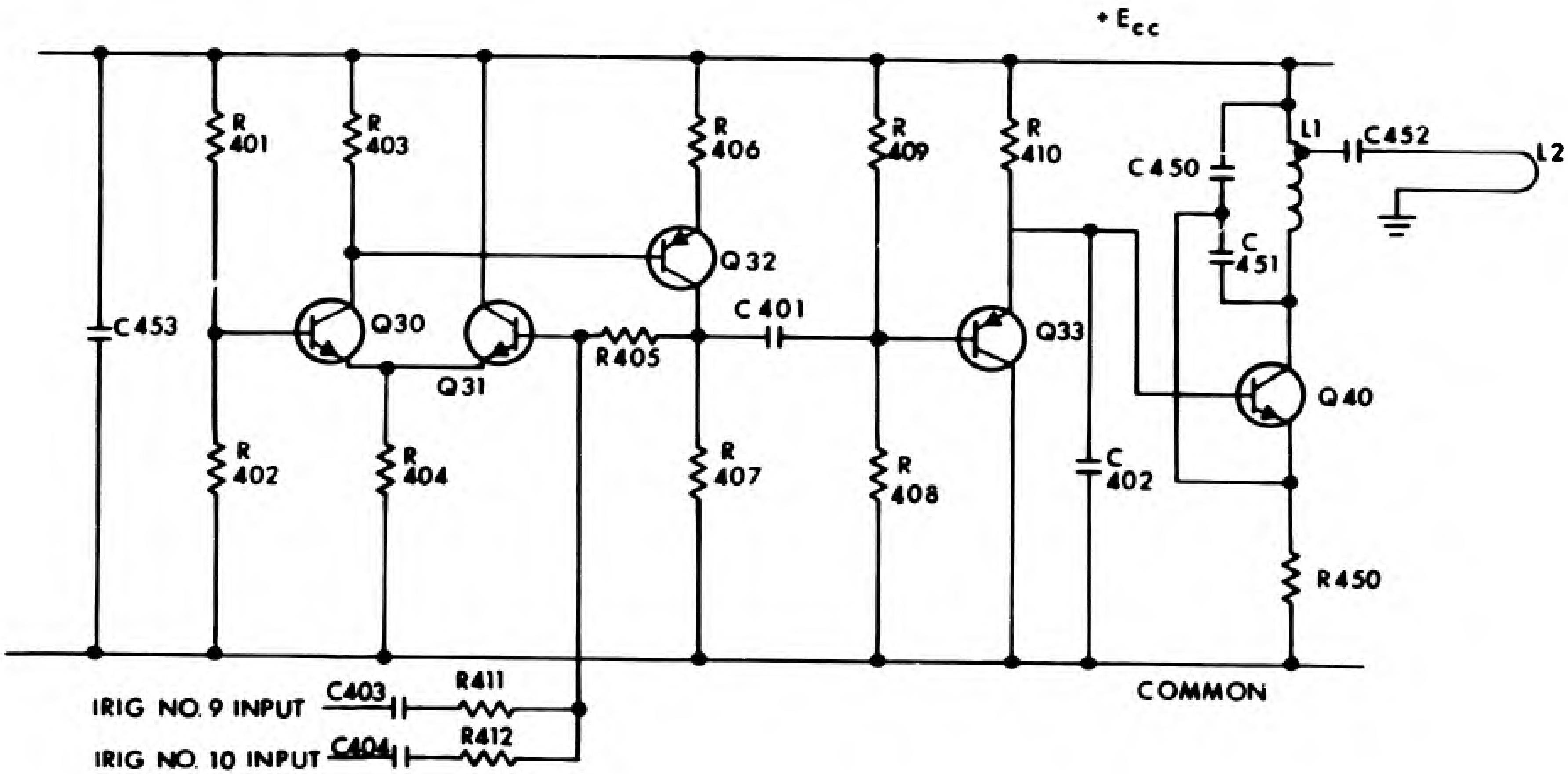


Figure 11. The Mixer, Driver, and VHF Oscillator.

This versatile amplifier consisting of three transistors, four resistors, draws about 15μA from a 5.4 vdc supply, and has an open loop voltage gain of about 800x.

4.3.4 BIOPOTENTIAL AMPLIFIER

The specifications required for this amplifier were as follows:

Input signal	1 mV p-p
Linearity	±5% FS
Frequency Response	2 Hz to 100 Hz
Common mode rejection	60 dB min.
Current drain	100μA (from 5.4 vdc)

About 100 mV was required to achieve ±7½ percent deviation of the channel 10 VCO. The maximum overall voltage gain of this amplifier should be, therefore, about 100x. A circuit meeting these requirements is shown in Figure 12.

The amplifier is most easily considered in two sections: a differential to single-ended unit forms the input, followed by an operational amplifier roughly similar to that described in Subsection 4.3.3.

The purpose of the first section, Q1 through Q5, is chiefly to develop the necessary common mode rejection, a low voltage gain is also obtained. Specifically:

Voltage gain	6.8X
Common mode rejection	90 dB
Output impedance	3 KΩ
CM range	2-4 volts
Current drain (3V cm)	11 μA

This first section is followed by an operational amplifier, the gain of which is given by the quotient of R119/R113. The gain required by this

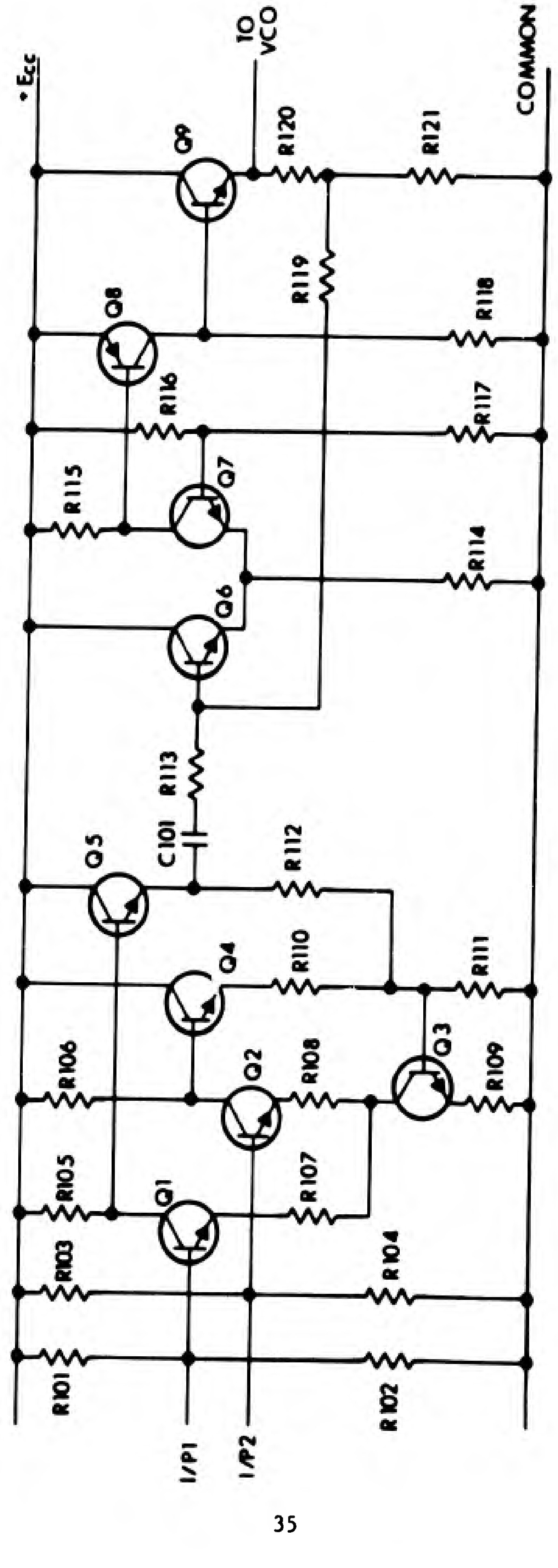


Figure 12. The Biopotential Amplifier.

section is about 37X and was readily achieved by the configuration shown.

It was at first planned that the channel 10 VCO would be driven directly from the output/feedback point of these amplifiers. When attempts were made to adjust the output level by varying one value of R116 and R117, the amplifier was found to have a stabilized dc output level. Three amplifiers tested at one time had natural output levels of 2.74 vdc, 2.77 vdc, and 2.76 vdc. In each case the channel 10 VCO required a potential somewhat greater than that provided. The resistor, R120, was added to raise the output level by depressing the feedback point; it worked well and adjustment of R120 remained an adjustment when setting up refined units.

The final amplifier drew a total current of 36μA from a 5.4 vdc supply (195μW).

4.3.5 THE REMOTE SWITCH

A schematic of this portion is shown in Figure 13. A negative trigger pulse from the first two stages is used to change the state of flip-flop, Q52, Q53. The pnp saturated switch, Q55, is driven by transistor Q54; the base series resistor, R511, is used to set the degree of saturation of Q55, about 25μA of base current is drawn giving a V_{CE}(sat) of about 100 mV for the switch.

It was originally planned to use a 60 Hz field to initiate the flip-flop state change. This proved to be unreliable in practice, probably because the size of the field initially produced was dependent upon the particular voltage phase existing at the time of switch closure. This problem was satisfactorily overcome by the use of a capacitive discharge approach. Instead of applying 110V rms to the excitation coil, about 600 Vdc was discharged through it.

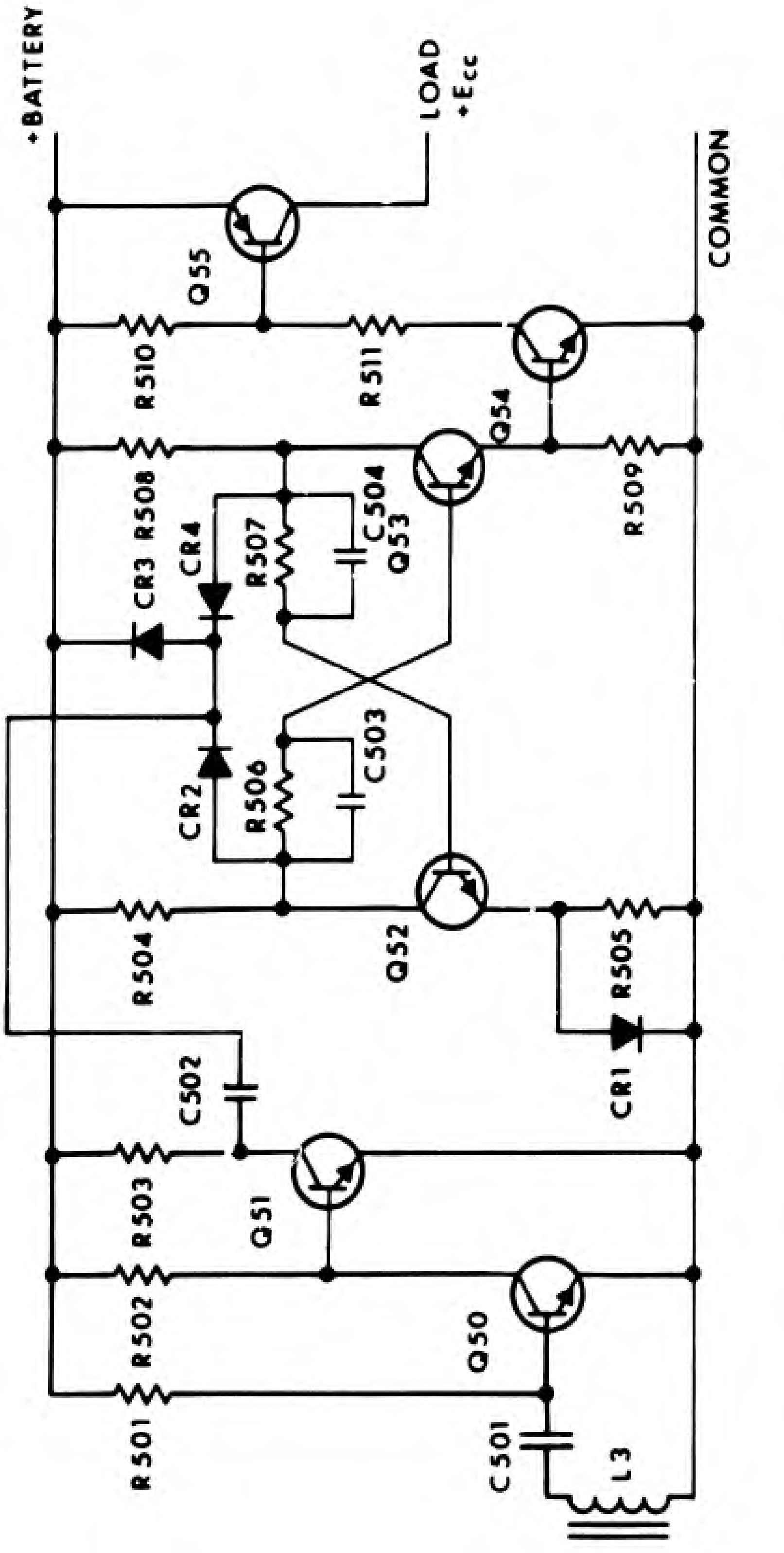


Figure 13. The Remote Power-Switch.

A new problem of switching contact bounce then became apparent. It was found that the flip-flop would track the pulses from the switch and the device would change state only if it sensed that the switch had bounced an odd number of times. This was cured by using a mercury wetted switch. Reliable switching is now obtained, in air, up to at least four feet without particular regard for the orientation of the sensing coil.

The sensing coil has about 1000 turns of number 44 wire on a small, laminated, iron core. Its overall dimensions are about 1.25 inches by 0.25 inch square and there were no physical problems in setting it in the final package.

In the OFF condition the switch draws about 12½μ A and a total of about 40μA in the ON condition.

4.3.6 TRANSMITTER

Excellent success had been obtained in the past using a straightforward Colpitts oscillator with frequency modulation applied to the base electrode. A modified Pierce circuit was also evaluated but was not stable through small temperature excursions. Since the supply voltage was at about 5.3 Vdc (allowing for the switch), and the maximum allowable dc input power is 2 mW, we may calculate the allowable collector current

$$I_c = \frac{2}{5.3} \text{ mA}$$

$$= 377 \mu\text{A}$$

A test was made to ascertain the sensitivity of this oscillator to modulation: it measured to be about ±1kHz deviation for an input of 1 mV p-p. Since MI of 1.4 had been chosen for each of the subcarriers, it was necessary to modulate the final by the following signal levels:

5.4 x 1.4 = 7.6 kHz for channel 10 corresponds to 7.6mV p-p
and
3.9 x 1.4 = 5.5 kHz for channel 9, corresponds to 5.5mV p-p.

4.3.6.1 Transmitting Antenna

The approach initially favored for this item was to use the actual conductor of the oscillator tank coil as the electromagnetic radiator. This method seemed to give the highest distant fields, however it was much more sensitive to stray capacitive loading and the like.

An antenna test range was set up on the roof of Ferber Associates, (Sherman Oaks, California). Two remotely rotatable antenna stations were located about four wavelengths apart (at 100 MHz), and on this range several transmitting antennas were tested. On this same range the crossed dipole receiving antenna with reflectors was optimized for the selected transmitting frequency.

A broad range of transmitting antennas has been evaluated (Figure 14); the largest was about 8 inches in diameter and the smallest was 1 inch in diameter. Practical considerations dictated that the actual antenna used would have about 3 inches as its maximum dimension. In Figures 15 and 16, polar plots are shown for three antennae, viz., a 2 inch and 3 inch diameter loop and a 2 by 3 inch elliptical element. This latter element is probably the most satisfactory from a packaging point of view and is seen to be about midway in performance between the 2 and 3 inch loop. No particular significance should be attached to the angle between the various patterns, it is probably a result of mechanical deficiencies in the test setup.

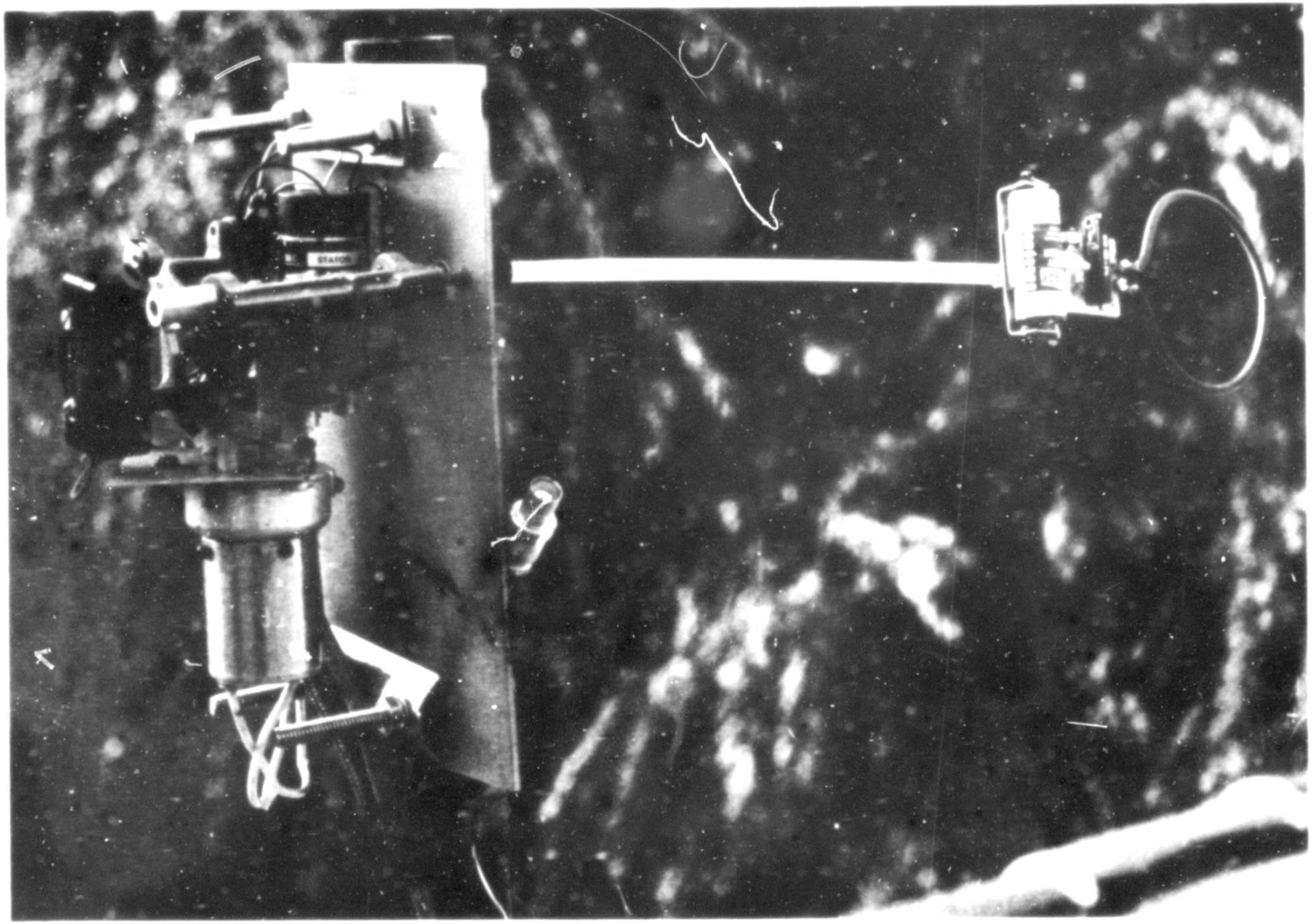


Figure 14. The Transmitter End of the Test Range. (The insulated shaft driver to the left shows the driving motor, limit switch, and remote angular indicator.)

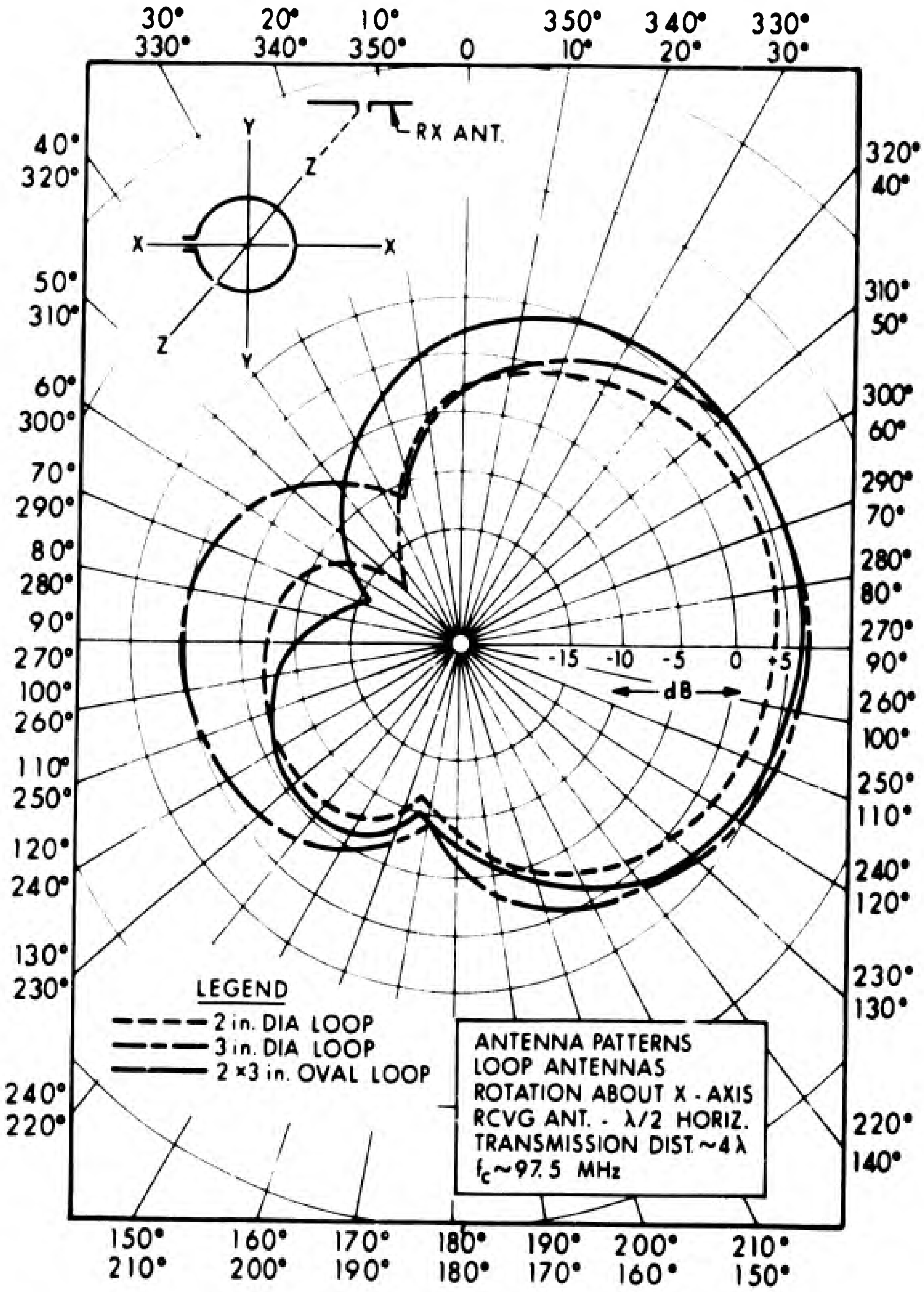


Figure 15. Transmitting Antennae Radiation Patterns (Various Antennae Sizes)

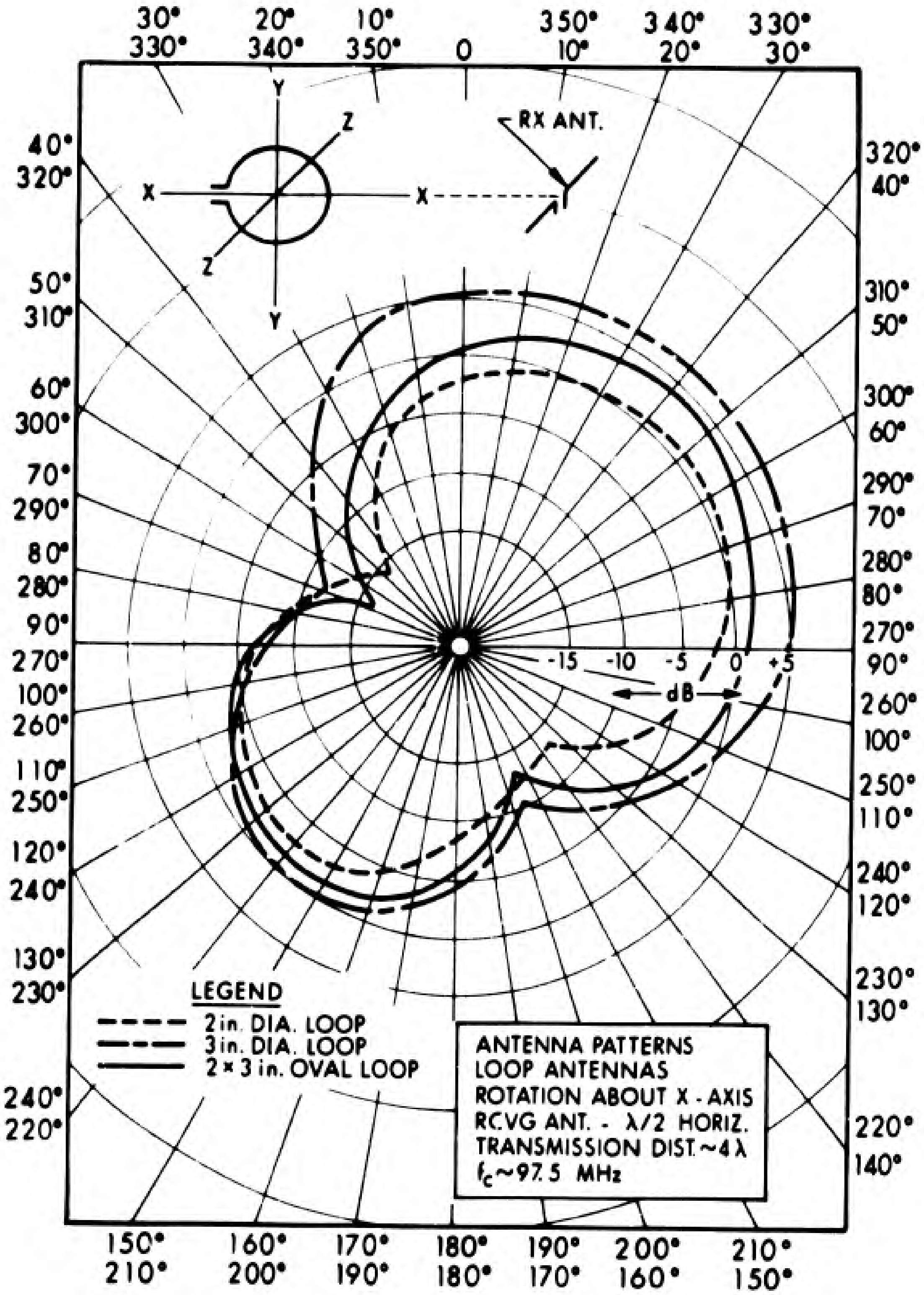


Figure 16. Transmitting Antennae Radiation Patterns (Various Antennae Sizes)

Packaging considerations dictate that the circuit and battery should be mounted within the actual radiative loop; Figures 17 and 18 show the effect of various combinations of constituent parts of the package inside the actual loop.

There are no real surprises in any of the data shown in the referenced figures; the data does, however, confirm what both theory and intuition would lead one to expect.

4.3.7 TRANSMITTER ANTENNA DRIVE AND ENCAPSULATION

The performance of the first prototype was a great disappointment; it was believed that part of the failure was attributable to the epoxy used for potting of the antenna. In order to clarify the effect of encapsulating a transmitting antenna, five identical ellipseswere made up from .053 inch diameter solid copper wire; four of the five were then encapsulated in various materials (Figure 19). Each was connected as the tank coil in an oscillator and the resonant frequency measured (Table III).

TABLE III

COIL DESIGNATION	RESONANT FREQUENCY (MHz)	DESCRIPTION OF COIL
A	143	Air core, no encapsulation
B	145	RTV -610
C	145	Biggs R290, ½ inch thick
D	149	Biggs R290, Thin Section (1/8 in.)
E	150	Biggs R290, 10:1 Eccosphere S1

To obtain unequivocal answers as to the effect of these various compounds on the field radiated from these elements, a series of tests was con-

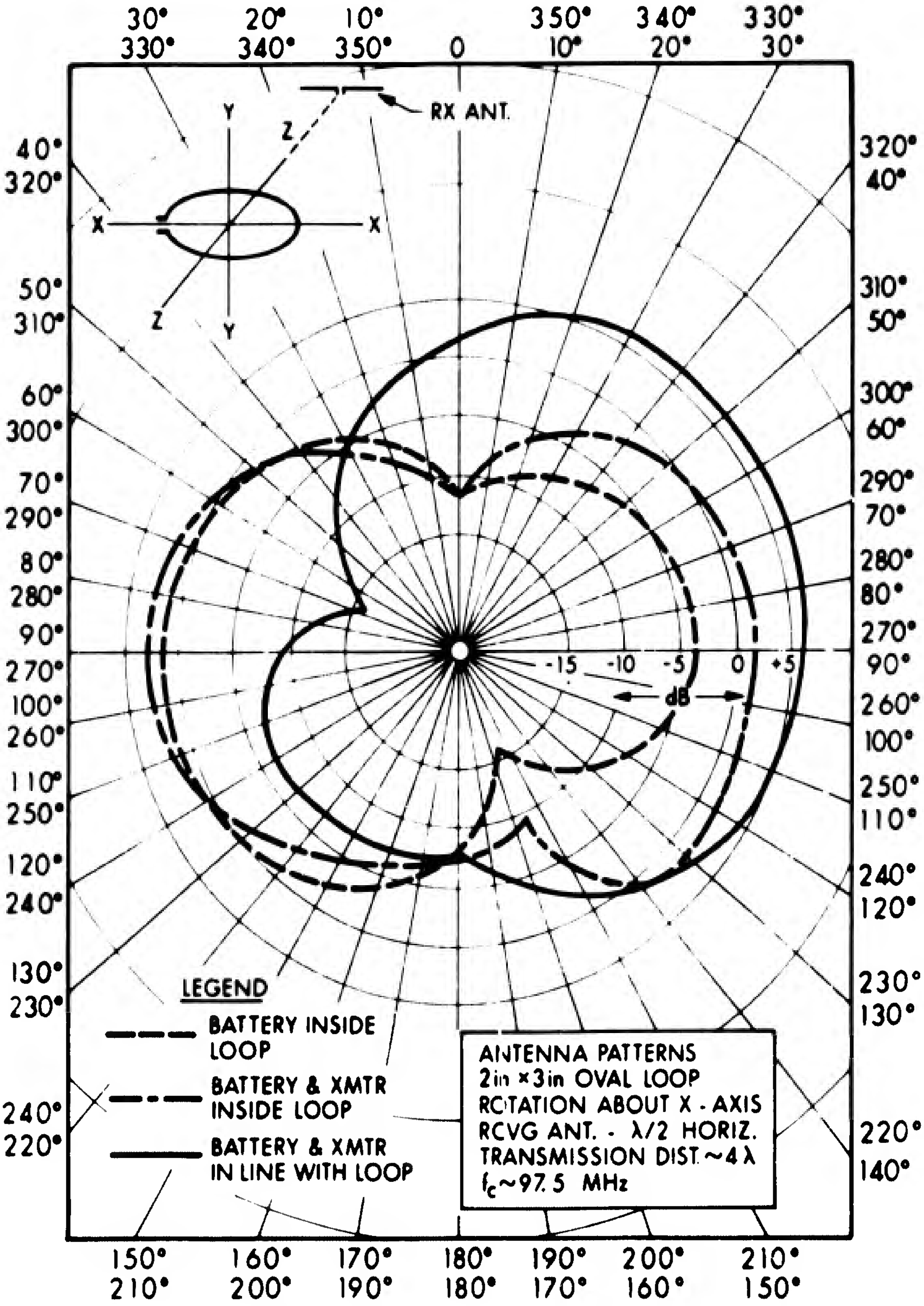


Figure 17. Transmitting Antennae Radiation Patterns with a Nearby Battery.

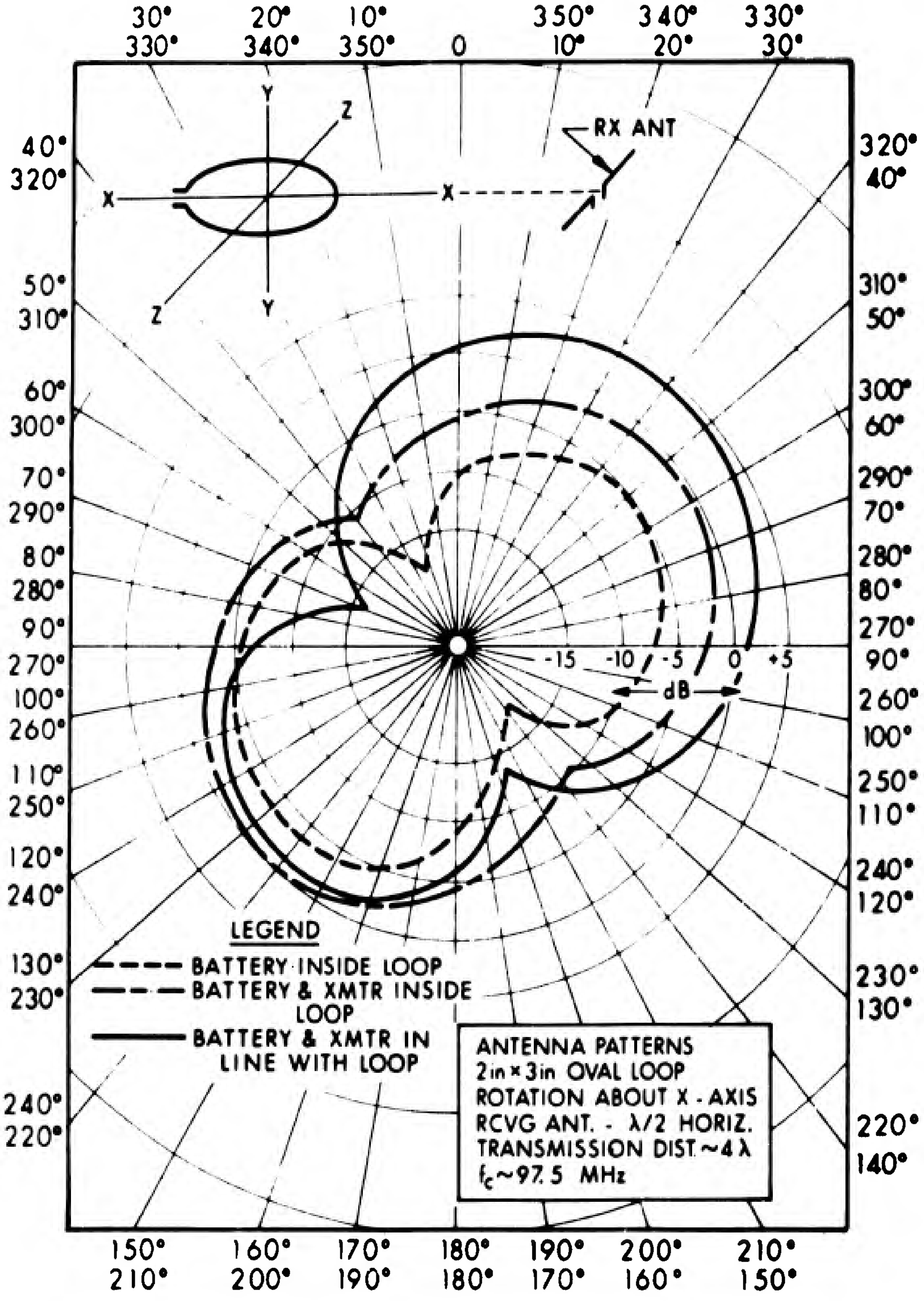


Figure 18. Polarization Effect on Transmitting Antennae of a Nearby Battery.

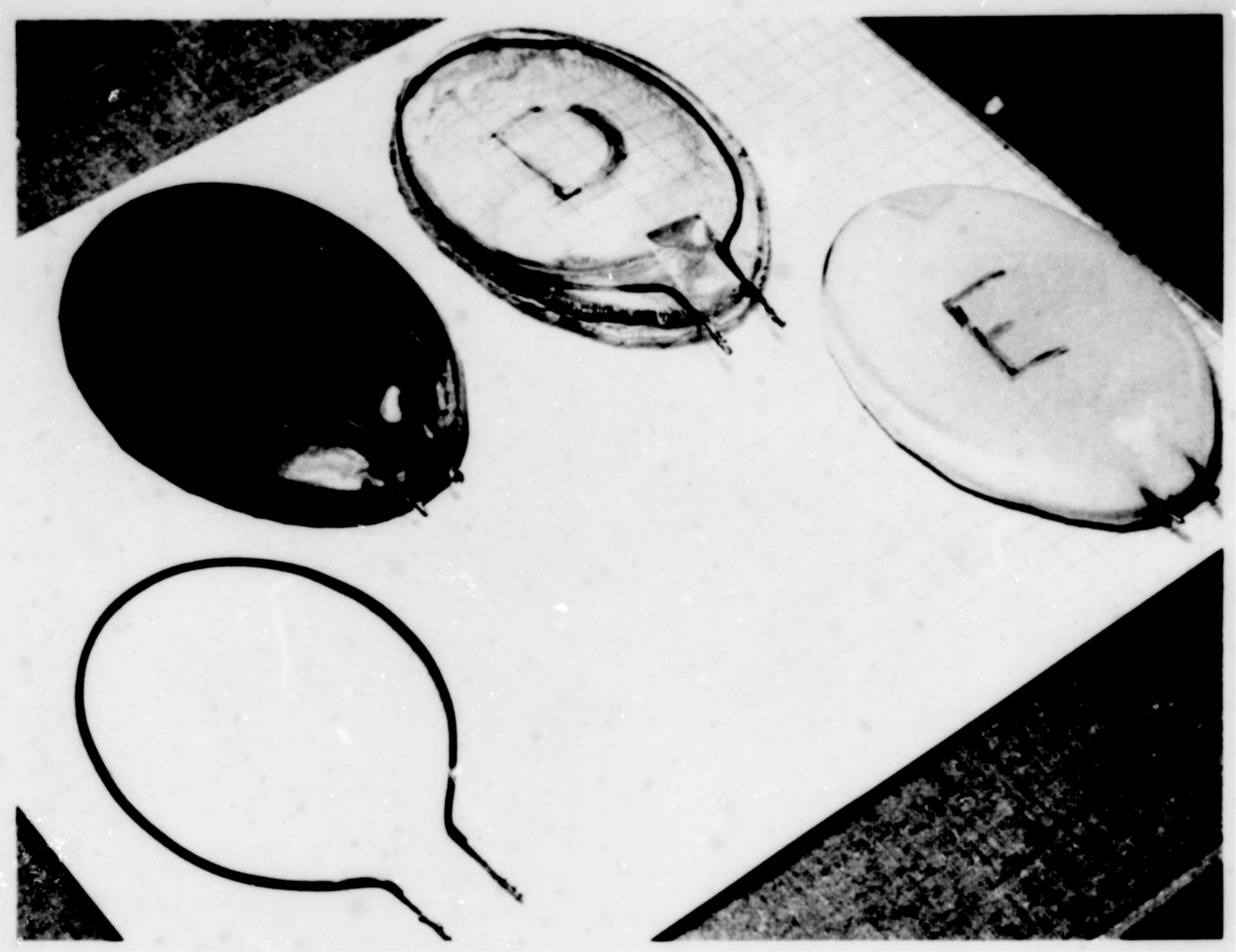


Figure 19. The Test Antennae. (Antenna "C" is shown in Figure 20. These each have the shape of the antenna used in the final instrument.)

ducted in Sepulveda Dam Basin, California. Each coil was driven, in turn, by a Colpitts oscillator similar to that built in the prototype; this oscillator was constructed on a breadboard, the antenna coil soldered in place (Figure 20) and the transmitter set up about 1½ meters above ground at a distance of 50 feet from the receiving antenna. The receiving antenna was resonated at 90 MHz and fed a Model NF105 Noise and Field Intensity Meter (Singer Metrics).

Axes of the antenna were chosen to be as follows:

z - z'	Longitudinal axis
x - x'	Cross axis in plane of the coil
y - y'	Normal axis passing through the coil plane

All coils were used with the same power and tuning setting, in Table IV the coils form the oscillator tank coil. This was termed the Radiating Resonant Loop.

TABLE IV

		FIELD STRENGTH 50 FEET			
COIL	FREQUENCY	x - x' db	z - z' db	z - z' μV	Noise μV
A	90.8 MHz	54	52	400	
B	90.3	54	53	425	
C	89.5	53	53	425	
D	88.5	55	53	430	
E	89.2	54	52	415	4

A series of tests (Table V) were then run using the tapped tank coil, the series coupling capacitor was roughly peaked for the first coil and left at that setting.

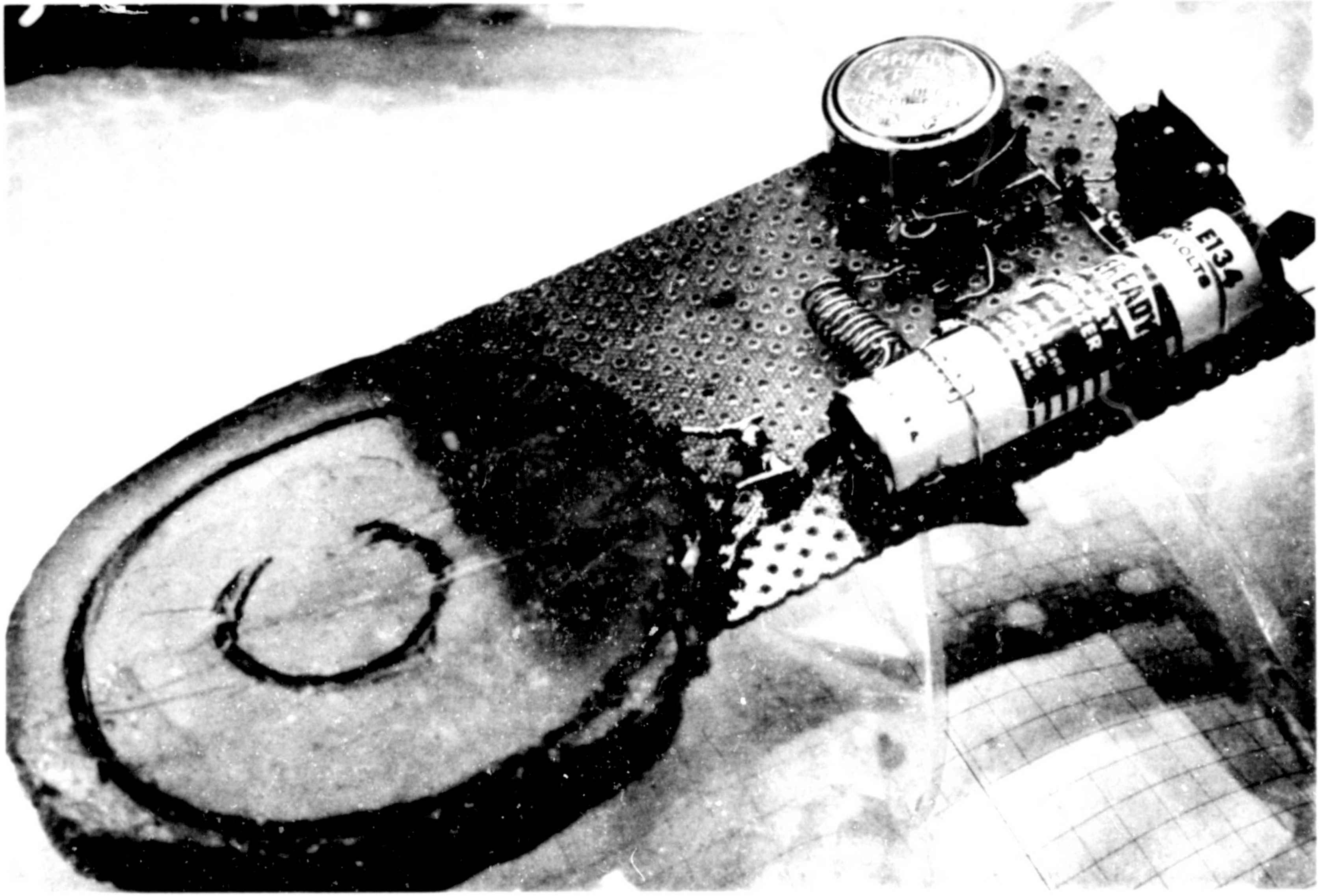


Figure 20. The Test Transmitters with the Tapped Tank Coil. (This is shown almost full size. The potentiometer was used to set the transistor bias and, thus, the dc input power.)

TABLE V

COIL	FREQUENCY	FIELD STRENGTH 50 FEET z - z' db	Peak Z db	y - y' db
A	85.8 MHz	44	46	32
B	87	40	44	
C	86	42	44	
D	91	50	53	
E	90	44	47	

It is suspected that the dc input power may have been set at an erroneously high level for the test of coil D. These tests were, generally, inconclusive; they did, however, furnish a qualitative guide as to radiation levels. The first lesson learned in this type of test series is the difficulty of obtaining conclusive, repeatable results unless a great deal of time and care are expended.

Highest field strengths were expected, at these low input power levels, in the instance of the transmitting antenna located in air. The test results are useful only as a reference since simulated physiological tissue placed in proximity to this oscillator-antenna proved its impractically.

On the antenna test range in Sherman Oaks (subsections 4.2.4, 4.3.6.1) interesting, qualitative data was obtained on a variety of transmitting antennae. It is suggested in this report (Section 6) that a future program could usefully be devoted to a study of this one area, viz., antenna for vhf transmission from a physiological situs. Neither time nor funds was available on this program for pursuit of this aspect of the design, although the limited results obtained were encouraging.

As previously mentioned, it was on the second prototype that it was decided to use an auto transformer for a more compatible impedance match from the oscillator tank coil to the radiating antenna. Mechanical and tuning considerations dictated that no more than about ten turns be used in the tank coil. The antenna was tapped at one-half turn from the power-supply end of the tank coil. Experimentation indicated that the tap point was not particularly critical; at the chosen point an impedance transform ratio (n^2) of 400 times would be obtained.

To promote maximum rf current transfer into the antenna a series capacitor was added at the point of connection to the tank coil. The effect of capacitance adjustment at this point was quite marked on the far-field strength. At the correct tuning point, the antenna inductive reactance would be exactly balanced by the capacitive reactance of the series tuning capacitor, encouraging maximum current transfer into the remaining pure resistance. In practice, the value of this capacitor above a certain value was not critical. This finding greatly simplified the setting of a reasonable optimum point of antenna tuning. The test circuit with which these facts were learned is shown in Figure 21. The practical embodiment is shown in Figure 22.

A field strength measurement at 50 feet of signal radiated from the tank coil alone gave a value 20 db below the approximately 50 db obtained from the series tuned antenna.

Los Angeles County water was used to simulate physiological tissue; rather than place the transmitter in a waterproof enclosure and immerse this in water, the water was placed in several plastic bags (two of which are shown in Figure 20) in which the test transmitter was then packed. A test was run to ascertain the effect upon field strength of variation of the antenna series feed capacitor; the test antenna was evaluated in both air and with the water bags packed around. The results are presented in Figure 23.

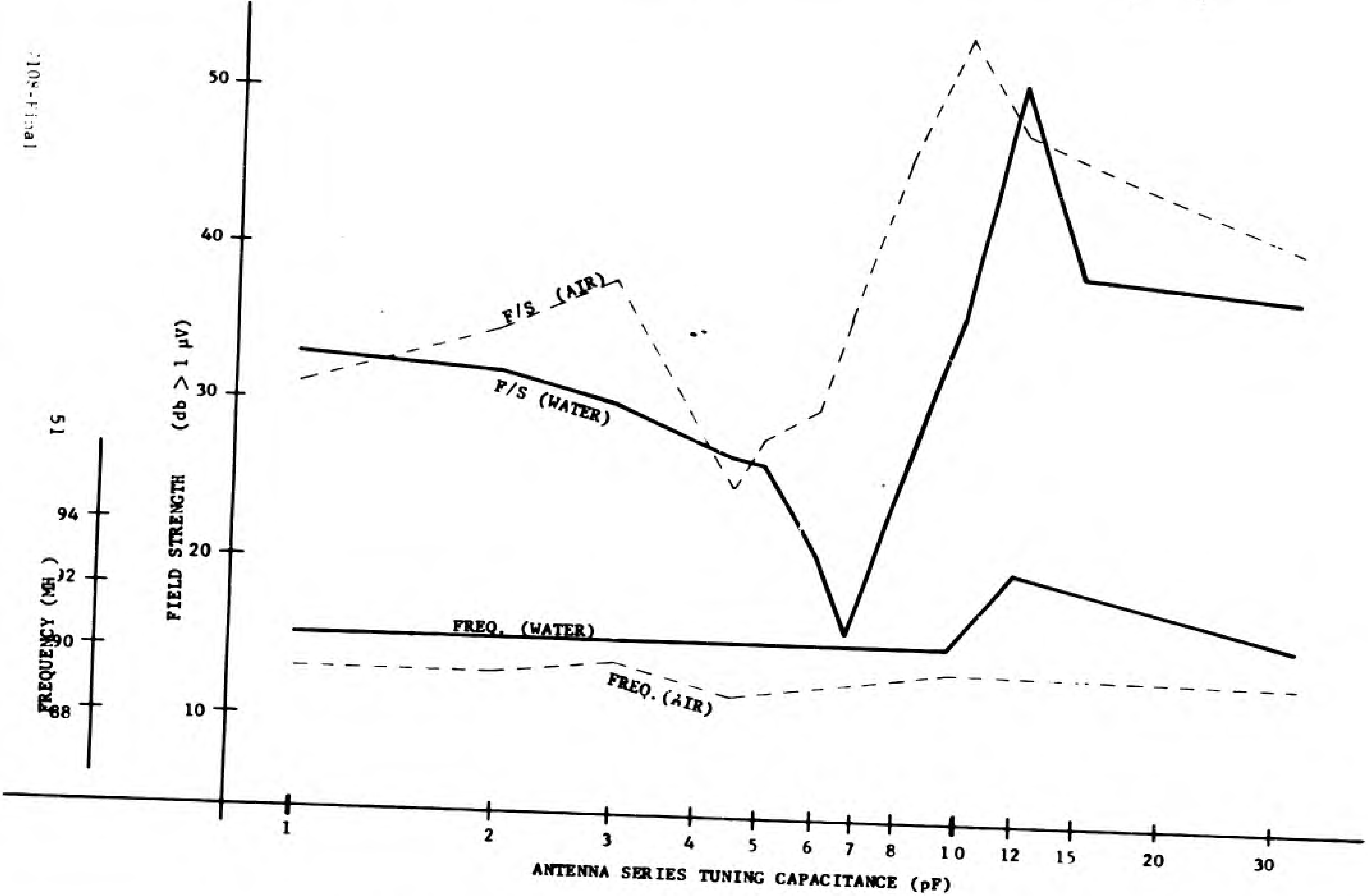


Figure 21. Transmitter Antenna Tests -- Data is Far Field, Relative.

Figure 22. The Penultimate Step to the Final Transmitter Configuration. (The tap is made at 1/2 turn from the undriven end of a 10-turn tank coil.)

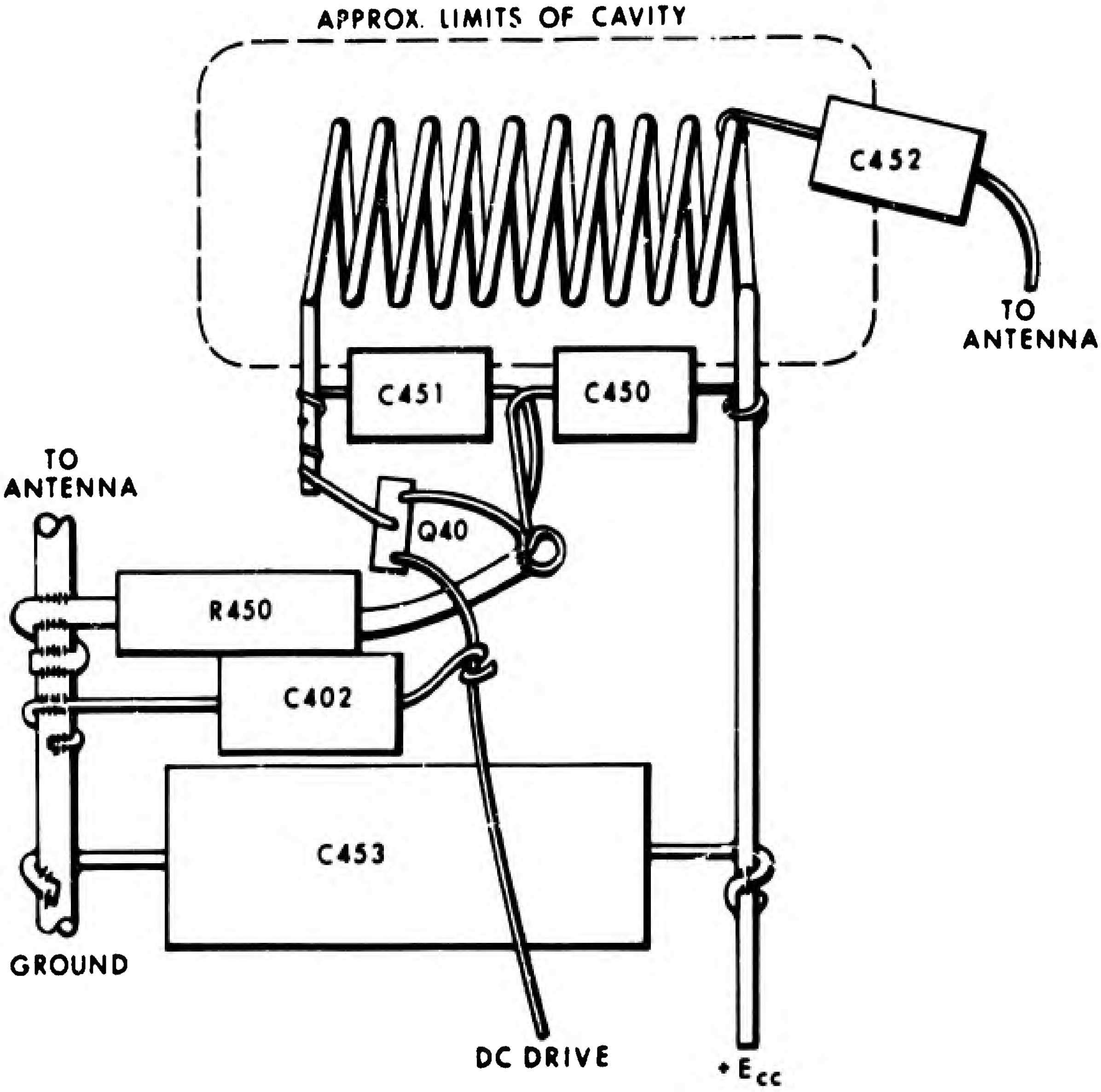


Figure 23. Transmitter Layout of the Refined Design. This is about 6 x full size.

Examination of this graph gives us two useful pieces of information: (1) that the field strength is not inordinately reduced when the radiator is surrounded by a slightly conductive medium and (2) that it would be well to assure that the coupling capacitor to the antenna is not less than 10 pF. Judging by the kink in the oscillator frequency in the water-surrounded case it would seem that the antenna series resonance was appreciably sharp.

4.4 THE PROTOTYPES

An initial difficulty experienced was the transmitter interface with physiological tissue. To minimize effects of this tissue upon the transmitter (loading, etc.) the antenna should be kept small but to maximize far-field strength the antenna dimensions should be as large as possible.

The attempt to fabricate the device in a single package, i.e., with the electrical battery close to the transmitting antenna caused additional difficulty. The loading effect of the conductive battery casing, originally expected to be significant, did not appear so; rather, the battery case, especially with the first prototype, was "hot" to rf and its capacitance to local conductive media was intolerable.

4.4.1 THE FIRST PROTOTYPE

Highest radiated field for a given power input to the implant final stage was highly desirable. This parameter was not, however, of single paramount importance. This particular truth was learned with the fabrication of the first prototype.

To achieve maximum rf field strength in the most straightforward manner, the approach applied successfully to many other researchers, that of using the oscillator tuned circuit to radiate directly, was attempted. No particular difficulties were expected since our breadboard tests of this approach, although indicating greater sensitivity to local conductive media, promised detuning of probably no more than 2 MHz after implantation (this step predates work of Subsection 4.3.7).

The completed package was to have two pairs of conductors brought out of the unit; the first, for input of biopotential, and the second, carrying the battery supply for subcutaneous location and subsequent provision of a direct ON/OFF switch. After this first unit was almost completed an extreme rf sensitivity of these outside leads was discovered; tests carried out on the breadboard had not indicated that these leads would be especially critical. The second area of extreme sensitivity was found to be the battery case.

LC filters and simple capacitive bypassing were used with limited success to desensitize the outside leads. It was found, however, that the battery sensitivity could not be appreciably reduced. Initial detuning of the rf carrier when the unit was placed in a water-filled container was greater than 10 MHz (cf, 2 MHz expected). Attempts to reduce the effect by increase of the package size proved to be ineffectual. Modulation indices of both the EKG signal and rf signal were quite accurately set at 1.4 (assuming an EKG upper frequency of 100 Hz on a 5.4 kHz subcarrier). The appearance of this first prototype also suffered since it was thought that a satisfactory package could be assembled without the making of special molds; this proved not to be the case.

The first prototype was delivered to the technical monitor at Holloman Air Force Base by the project manager of EOS. The instrument was not suitable for implantation however, for several reasons. The more significant of these were as follows: it was considered to be too bulky; the surface finish was not sufficiently smooth; the Dacron mesh for anchoring of the implant was too closely trimmed to the outline of the package; and the epoxy used for the encapsulation was flaking from the Dacron mesh.

Several factors led to the unsatisfactory performance of this first article. These mostly concerned the differing conditions under which the breadboard evaluation tests and the prototype tests were conducted. For example, the epoxy used on the prototype caused a considerable change in the performance of device; also the battery used in the instrument was "hot" with rf signals. In addition the power leads brought out for the subcutaneous power switch could not be effectively decoupled from rf currents.

Finally, with regard to this visit to the customer's facility, the verbal interchange with various personnel there, particularly Major J. Fineg and Mr. R. Chandler, proved to be construetive and most helpful.

4.4.2 THE SECOND PROTOTYPE

There were three key shortcomings on the first prototype that required correction:

a. Sensitivity to detuning
b. Surface finish unsuitable for implanting
c. Insufficient area of Dacron for attachment.

The detuning problem of the antenna was cured by means of the auto-transformer coupling. The presence on the battery of troublesome rf currents was cured by a different approach to decoupling, both with regard to the bypass capaciter placement and the size of the grounding leads.

The associated circuits for the second pretotye, viz., ekg amplifier, channel 10 subcarrier oscillator, band pass amplifier and summer, were assembled using the soldered cordwood technique of the EOS telemetry product line. An example of this type of fabrication is shown in Figure 24.

The whole package was assembled into a rigid structure (Figure 25) located in the center of a large sheet of Dacron (Figure 26) and encapsulated in hard epoxy (Biggs Green 109) (Figure 27).

Vacuum formed cellulose formers were used, as previously mentioned; some difficulty was experienced with incompatibility between the adhesive used to seal these formers and the epoxy used for the encapsulation. The effect of this incompatibility was that the adhesive, initially clear, turned a rusty brown.

The modulation indices for the subcarrier oscillator and the rf carrier were set equal to 1.4 and tests augured well for the implantation and field test.

The epoxy used was unfilled and very hard; the first sign of trouble was failure of the channel 10 subcarrier oscillator, although the rf oscillator still worked well. A measurement was made of current drain in this partially failed condition, and instead of the 400μA expected, the reading was about 1400μA. There were, apparently rather more serious problems than a simple failure. Before this failure could be clarified or ameliorated, the rf oscillator also failed and the unit was scrapped.

4.4.3 THE THIRD PROTOTYPE

The first two prototypes had been built with complete electronic signal conditioning to allow telemetry of ekg. The fabrication of these circuits was time consuming. In order to expedite fabrication of an instrument for field strength testing, the requirement for

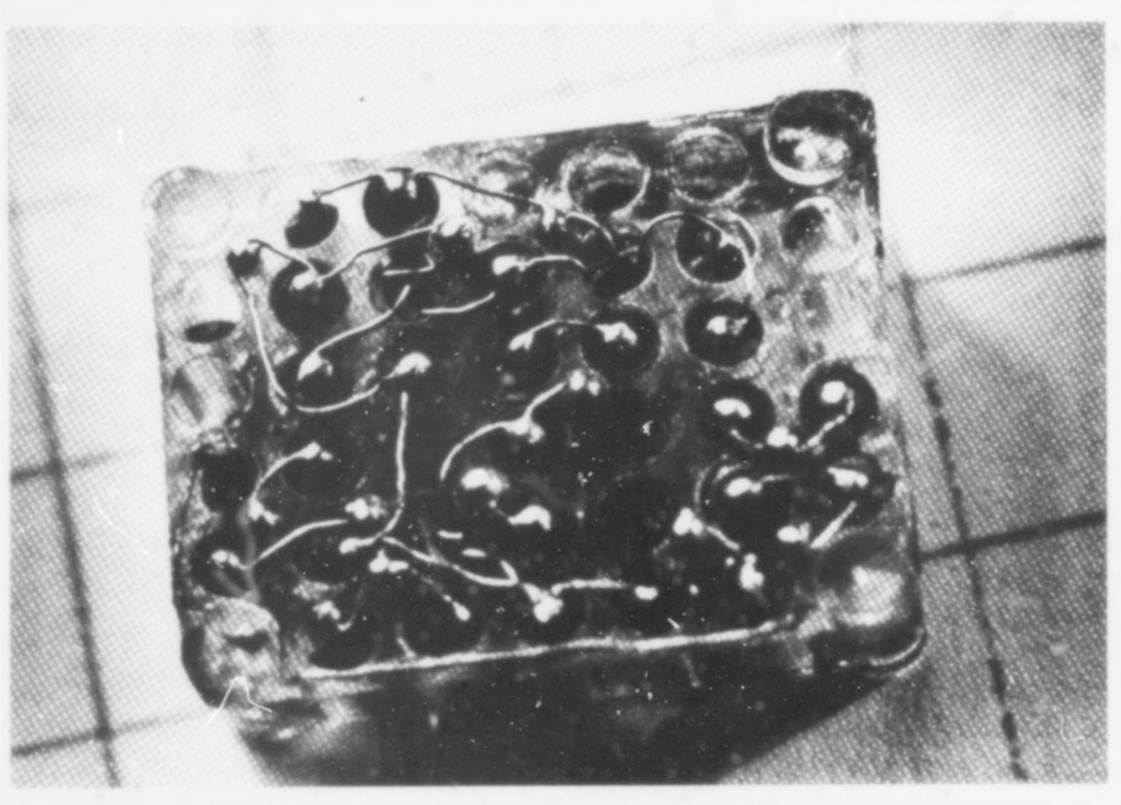


Figure 24. A Soldered Cordword Assembly Shown on a Background of 1/4-inch Squares.

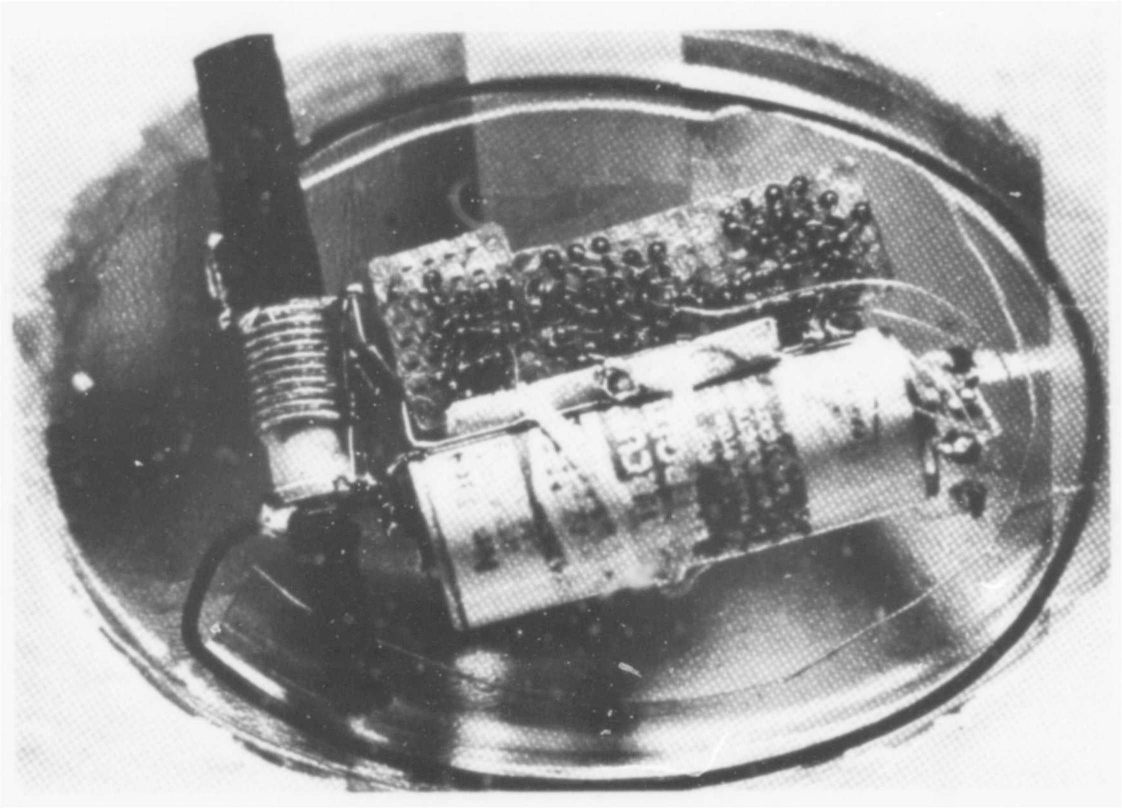


Figure 25. The Second Prototype Immediately Prior to Encapsulation. (The four sections of circuitry shown are, from right to left, the EKG amplifier, IRIG channel 10 VCO, mixer, and VHF oscillator - adjacent to the coil.)

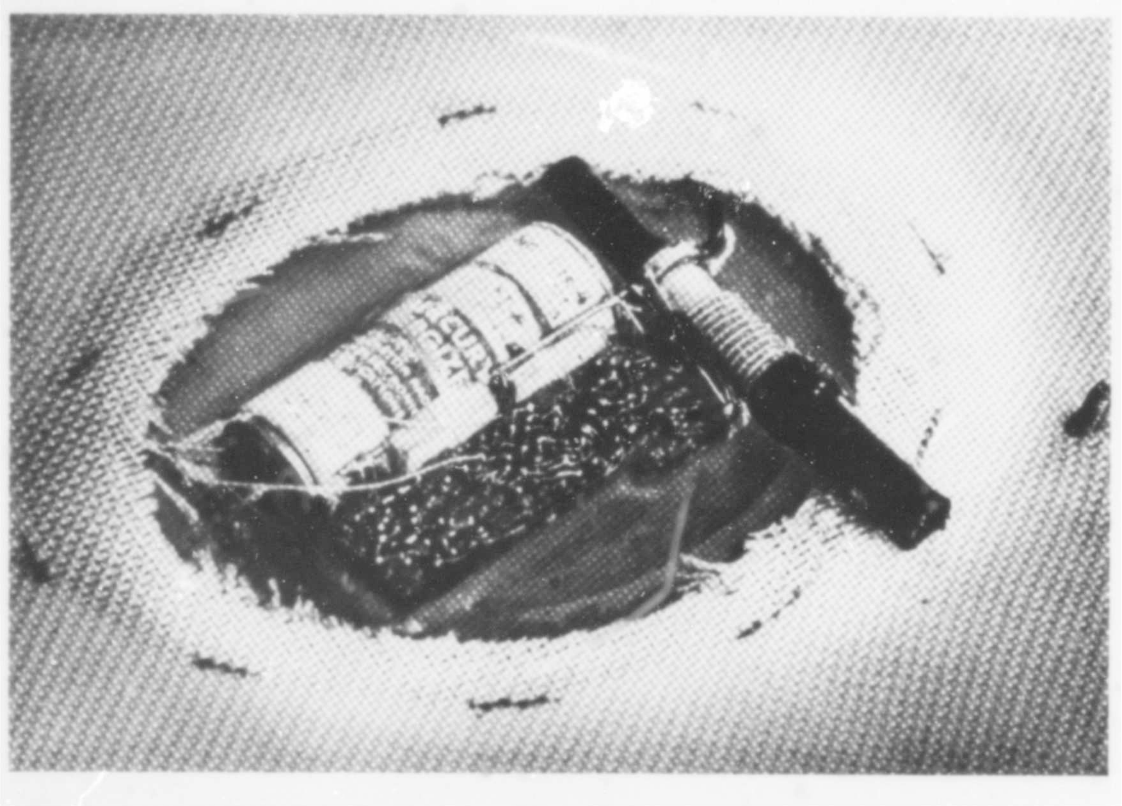


Figure 26. The Second Prototype, Half Encapsulated, as the Dacron Sheet was Added.

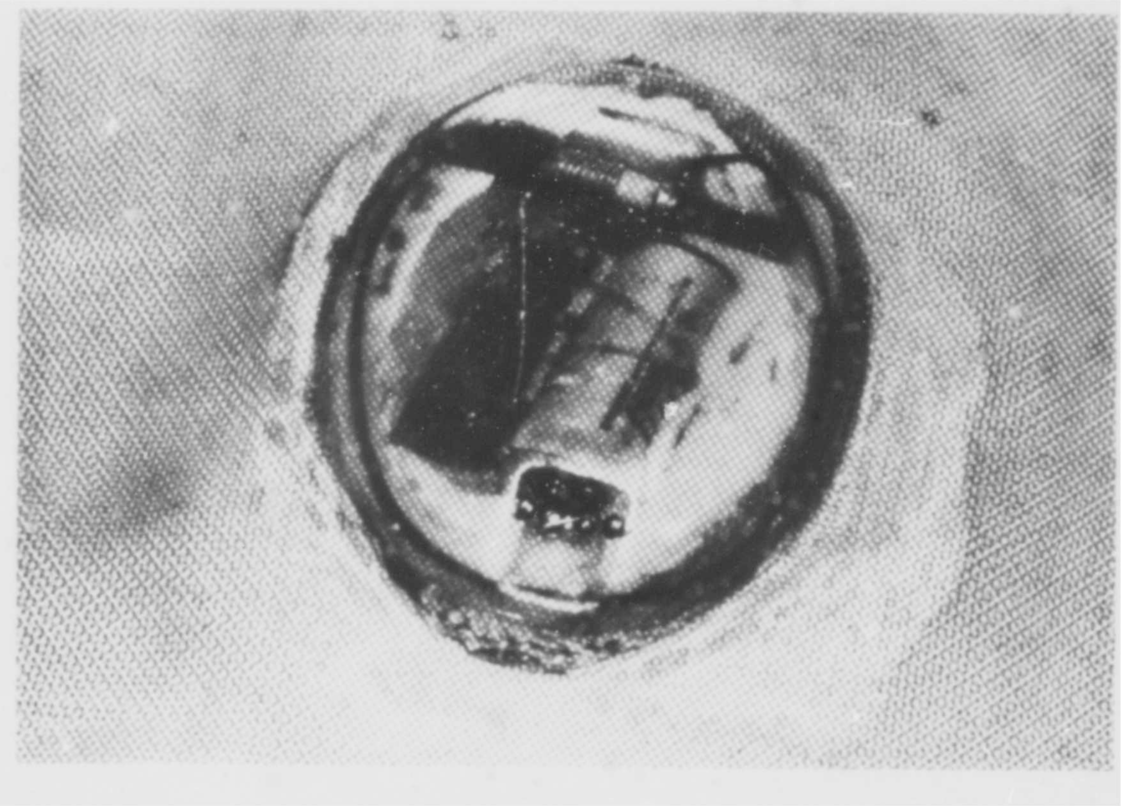


Figure 27. The Complete Second Prototype. (The positive bus-bar may be seen connecting the battery to one end of the tank coil.)

inclusion of a telemetry channel with the prototype was waived, on March 21, 1967. The third prototype was then assembled and a vacuum formed subenclosure was used for housing of the electronics. This subenclosure was filled with RTV rubber to prevent damage to the electronics due to strains and forces generated by a hard epoxy.

The hard epoxy used in the outer coating was this time filled with Emerson and Cuming, Inc. Eccospheres S1 to reduce the effects upon the rf circuitry.

The vacuum formed subenclosure proved most practical, so similar enclosures were used on the outside surface of the instrument. The entire package was sealed with parafin wax prior to filling with epoxy; this wax was also used to impregnate the Dacron mesh and prevent the epoxy wicking into the fibers with subsequent stiffening and flaking.

This procedure worked so smoothly and well that it was followed without change on the four refined units.

4.4.4 PROTOTYPE FIELD TEST

The field test of the prototype was conducted at the customer's facility. A copy of the details of this checkout is included, in its entirety, below:

> CHECKOUT OF E.O.S. PROTOTYPE IMPLANT
>
> "The EOS prototype telemetry unit was received on 8 May 1967. Due to scheduling difficulties (overload on limited veterinary staff), it was impossible to schedule the implant before 23 May. The receiving system was delivered on 15 May, was assembled and tested and the package was tested by 19 May. An attempt was made to implant the package during another operation on 23 May, however, difficulties encountered in the prime operation made it impossible. TDY commitments delayed rescheduling until 5 June. During this implant, one of the battery wires

broke off inside the silastic coating. The break was repaired by (1) removing the silastic holding the wires in place, (2) stripping, tinning, and soldering the two wires (the other wire was broken during the repair), (3) placing a 2½ to 3 inch length of silastic tubing over each wire for strain relief and, (4) resealing with silastic.

"By Tuesday the 13th (June 1967), the implanted dog, a small beagle, was in condition to run the required tests. These tests were made with the dog in the bed of a ½ ton truck (it would not walk on a leash) with the truck being driven inside the fence but outside of the "island." Signal strengths were read off the microvolt meter of the Nems-Clark R-1037F receiver and compared with the known signal strengths of two local F.M. stations. Receiver background noise was also measured by this method, and agrees well with calculated theoretical values (-81 to 84 dbm measured verses -83.2 dbm calculated). The highest filed strength measured was between 10 and 20 microvolts per meter at a range of approximately 16.5 meters. In general, the signal plus noise to noise ratio was between 3 and 7 db all around the consortium, except the furthest point where it was between 2.4 and 5.4 db. Meter readings were as follows: (1) noise 10-20μvolts, (2) general readings 40 to 50μvolts and, (3) far end reading 35 micro volts. The far end readings are undoubtedly pessimistic since the animal was in a truck, and there is a small rise in the land between the consortium building and the far end. During all phases of testing, the antenna was pointed directly at the animal with the implant package.

"Due to the increased sensitivity of the equipment over that previous used, a few previously unheard F.M. stations were found. These frequencies are: 88.125 MHz, 94.284 MHz, 94.687 MHZ, 94.904 MHZ*, 99.900 MHz, 102.321 MHz and 103.9 MHz. The frequency marked with an asterisk is KXXI, nominally at 94.5 MHz.

Note that there is another local (El Paso) station normally above KXXI, but it could not be found due to interference.

"It was discovered on the 15th that the dog had chewed off the tape protecting the battery wires and had chewed these wires off. Since the field strength tests are essentially complete, no attempt was made to reconnect the system. The package has been left in the dog to check on tissue reaction."

This report was written by Harold A. Cray, GS-11, of the Bio-Effects Division. It remains to add that dc current drawn by this prototype transmitter was 375μA at about 5.6 vdc, corresponding to a power level of 2.1 mWatt.

4.5 THE REFINED TRANSMITTER

Most of the details of the thought and practice that went into making up one of these transmitters has already been set forth. In this subsection the picture will be completed by working through the step by step setting up of one of the final units. Serial Number 4 is chosen for this worked example. The procedure was to hook up the complete unit on a breadboard and set all the variables; the subcircuits, and chosen resistors and capacitors were then transferred to the subassembly holder and all interconnections restored, the unit was then sealed in RTV-11, waxed into the final vacuum formed covers and filled with regular epoxy.

Serial Number 4 will now be described in detail (with actual data).

4.5.1 SETTING UP

At this point all individual modules (Figure 28) have been checked for correct individual operations and salient operating features.

a. Check Channel 10 VCO

Excitation 5.359 Vdc   Current Drain 48μA   Freq. ≈ 5.4 KHz

Peak band pass response noted at 5.52 KHz

Nominal frequency of 5.391 KHz obtained with input of 3.15 Vdc.

Natural output of ekg amplifier S/N 4 2.77 Vdc.

b. Set ekg Amplifier Output Level

$$R_{120}^{*} = \frac{3.15 - 2.77}{2.77} \times R_{121}$$

---

* See Figure 12

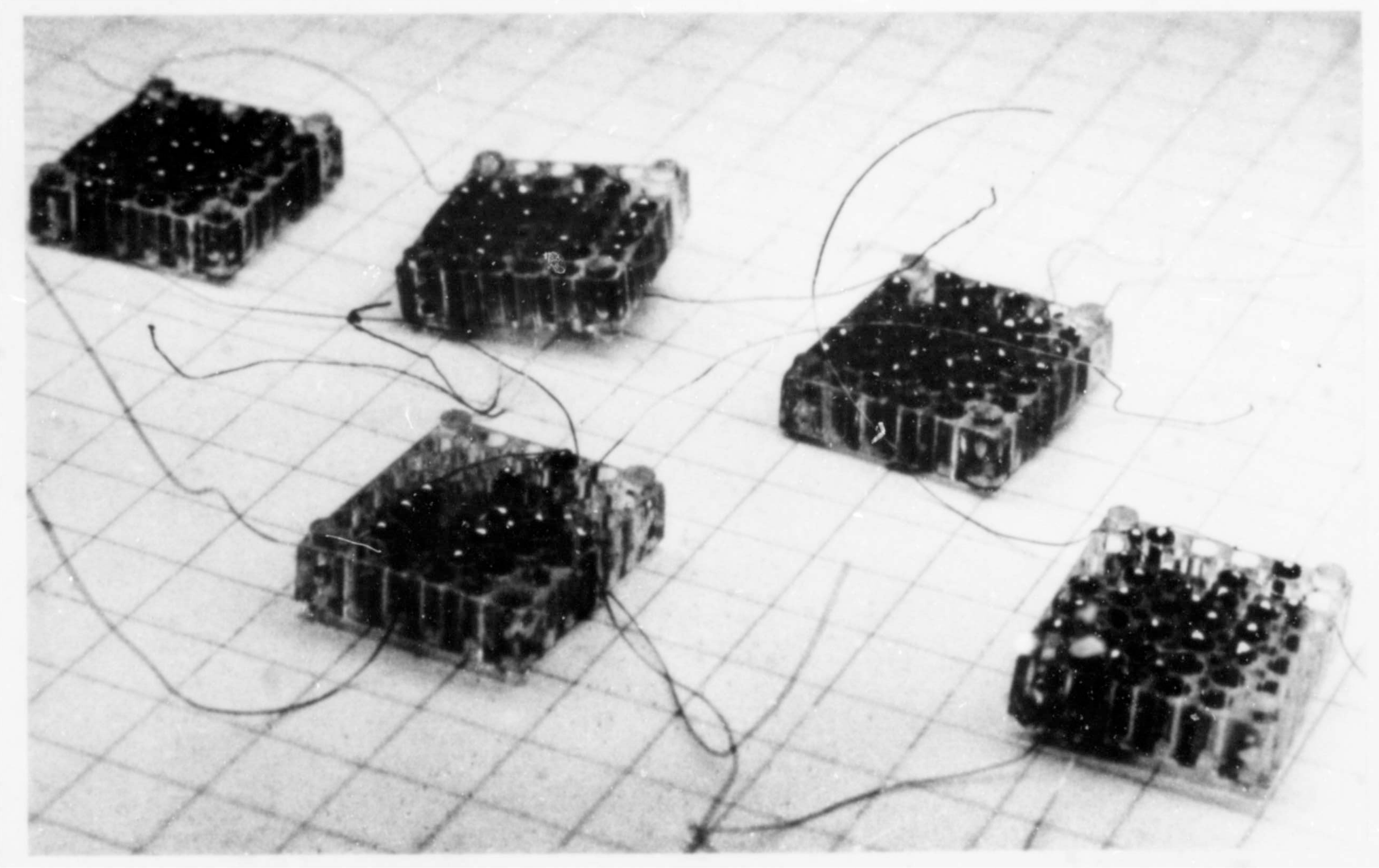


Figure 28. The Electronic Subassemblies of a Final Instrument. (The background is 1/4-inch squares.)

$$= \frac{.38}{2.77} \times .22 \approx 30\ \mathrm{K}\Omega$$

Eventually installed a 39 KΩ in position R_{120} to give an output center frequency of 5.433 KHz.

c. <u>Set Channel 9</u>

R_{330} set at 7.5 MΩ

R_{331} set at .39 MΩ

Criteria of this choice is that the parallel combination must be about 0.4 MΩ to give the correct sensitivity and, together with the thermistor, the supply must be divided to a level such as to give the desired output frequency at the particular setup temperature.

d. <u>Transmitter Connected</u>

Bias point for the follower, Q33, was set to give a dc input current to the final of 400μA (corresponding to 2.16 mW).

Bias voltage noted at 1.008 Vdc.

R410 set to be 0.82 MΩ

R408 calculated to be 0.186 MΩ

Set at 180 KΩ gave current of 385μA

Set to 200KΩ gave current of 425μA

e. <u>Set Subcarrier Mixing Levels</u>

Set R411 and R412 to give subcarrier levels of channel 9 at 5.5 mV p-p and channel 10 at 7.5 mV p-p respectively.

Checked frequencies: Channel 9 3.417 KHz
Channel 10 5.412 KHz

f. <u>Remote Switch Operation</u>

The check for this portion of the circuit simply consisted of connecting in the switch module and operating the exciter three to four feet away -- if the switch generally worked (0.9) it was considered good.

4.5.2 ASSEMBLY

At the end of the setting up process all the subcircuit carriers have been arranged on a breadboard and the necessary discrete components added externally (Figure 29). Up to this point the battery to be finally packaged has never been used.

The individual subcircuits are then all placed in the vacuum formed carrier and reconnected as previously, but this time in the final physical configuration (Figure 30, 31). The antenna is made of enamel-coated solid copper wire of 0.083 inch diameter.

The circuit carrier was next covered with a mating half, the edge was heat sealed, and it was filled with RTV-11, all except the volume enclosing the tank coil which was left in air. It was found, with the first prototype, that epoxy in intimate contact with the tank coil spoils the circuit "Q" and severely effects the efficiency of the vhf oscillator.

This subassembly was then positioned, with the Dacron cloth, in the outer carrier, the whole was sealed up with parafin wax and filled with Biggs R290 resin and C512 hardener. This epoxy was filled with 10 percent, by weight, of Emerson and Cuming, Inc. Eccospheres S1.

After curing in a water bath necessitated by the severe exotherm of the Biggs epoxy, the package was cleaned of wax under hot water. The final unit is shown in Figure 32.

4.5.3 FINAL TEST RESULTS

As may be seen in the photograph of the final unit, ready for shipment, a small terminal board was added. The outer terminals are for the biopotential input whilst the inner pair form a break in the lead

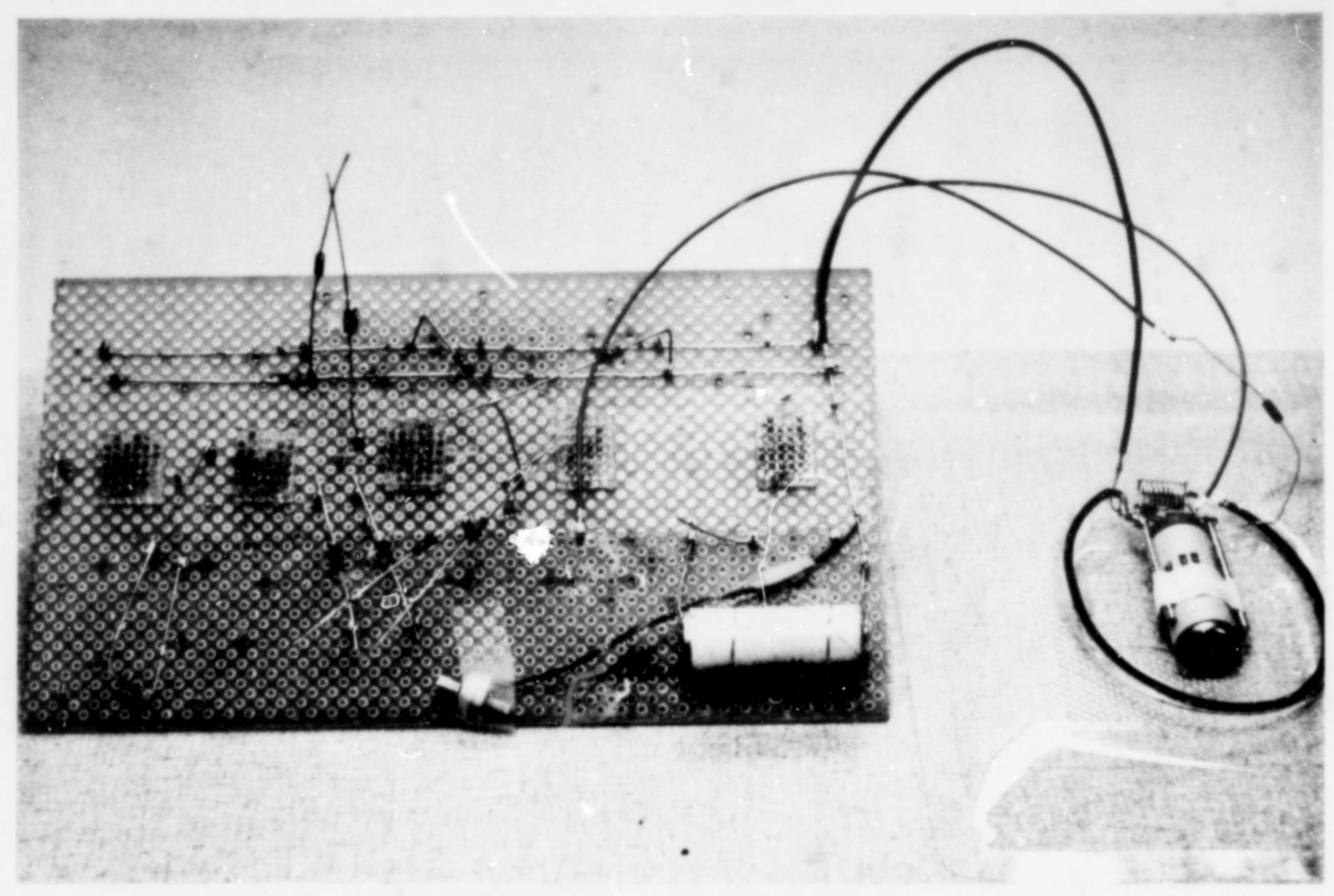


Figure 29. A Refined Transmitter Ready for Final Packaging. (The three leads to the oscillator are positive supply, common and drive, note the "stopper" resistor necessitated by the long leads of this configuration.)

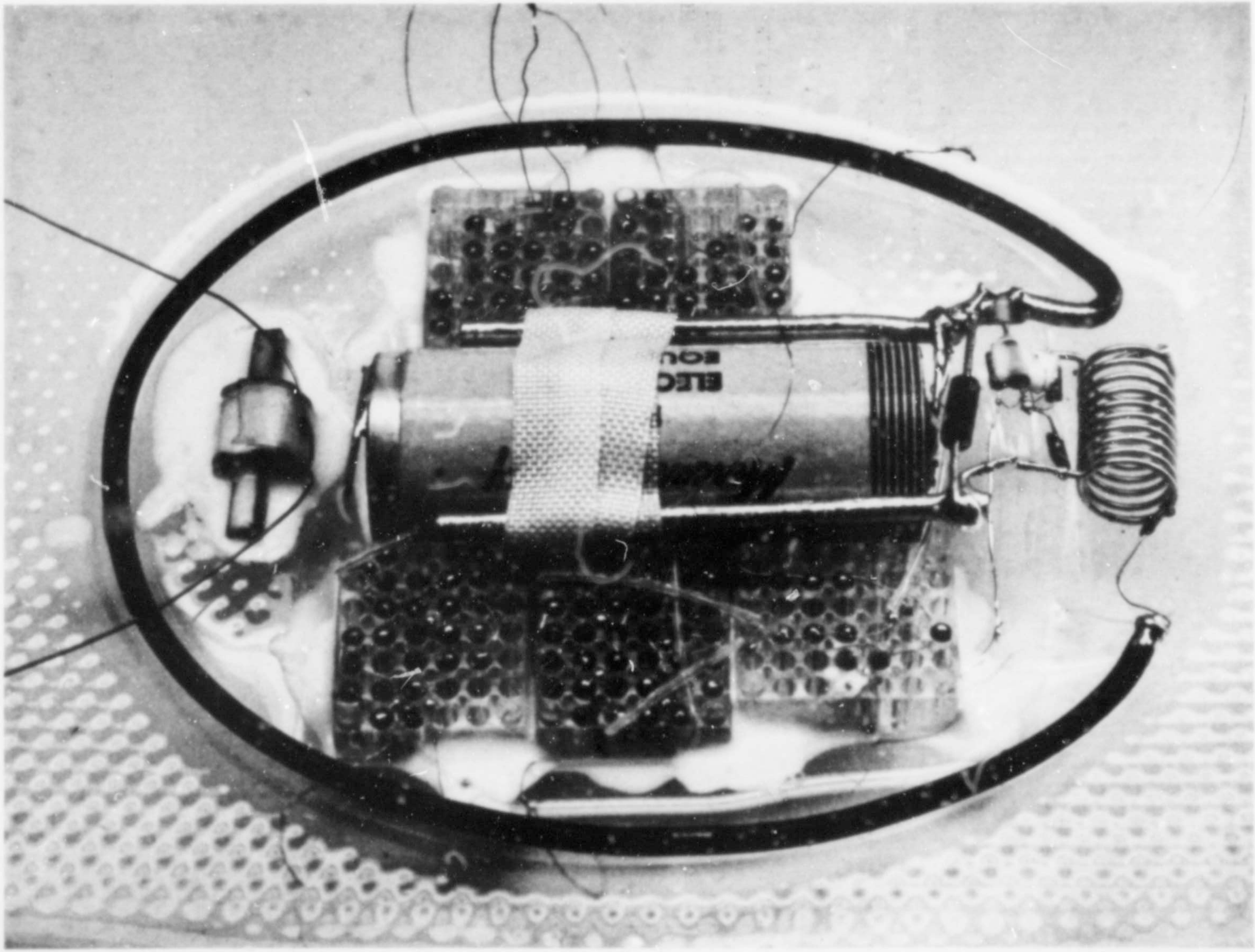


Figure 30. A Refined Transmitter, Partially Interconnected. (Note the heavy copper bus-bars and decoupling immediately adjacent to the VHF oscillator.)

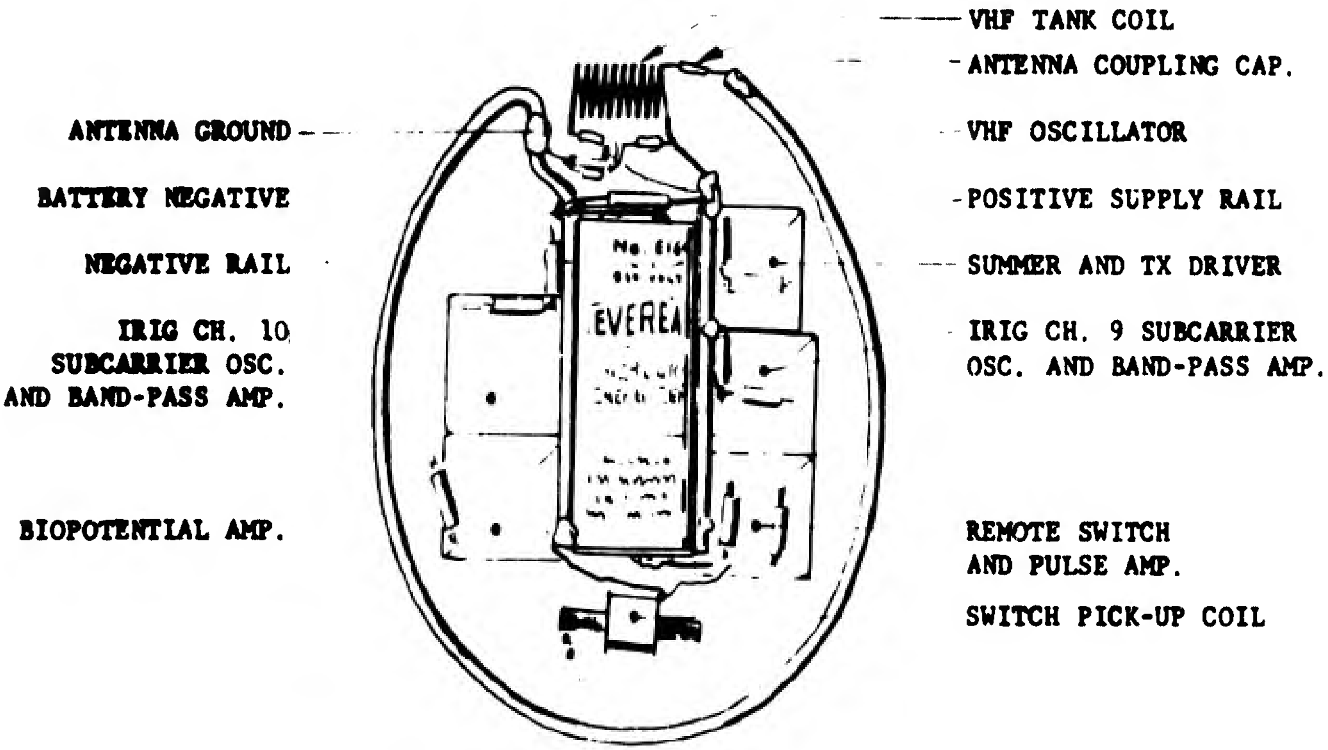


Figure 31. Subassembly and Component Placement of a Refined Transmitter (Full Size).

Figure 32. Refined Transmitter Number 3 as it Appeared Immediately Prior to Shipment. (It is shown here approximately full size with the 30 x 40 cm Dacron mesh folded beneath. The depression on the surface holds two biopotential sensing connections and two power terminals to be shorted together to energize the instrument; this depression is filled with RTV rubber prior to implanting.)

from the positive of the battery to the remote power switch circuitry. Prior to operation a jumper would be soldered between the center terminals and suitable biopotential leads connected to the outside pair; the depression should then be filled, and sealed, with RTV rubber.

Connection of a current meter between the center terminals permits the OFF or ON current to be measured.

Summation of data for the four refined transmitters is presented in Table VI. The frequency of the channel 9 VCO is read at room temperature rather than at some stabilized condition.

TABLE IV

	Current		Calc.	Carrier VHF	IRIG	IRIG
Serial No.	Off	On	Lifetime	Freq.	Ch. 9	Ch. 10
Design Goal	10μA	1100μA	30 days	88-108	3.9 KHZ	5.4 KHz
1	12.5	670	31.1	88.5	3.67	5.39
2	12.5	655	31.8	89.1	3.52	5.37
3	12.5	645	32.3	88.0	3.44	5.41
4	12.5	610	34.2	90.1	3.67	5.43

IRIG channel 9 has a center frequency of 3.9 kHz. In this particular application the steady frequency is a measure of ambient temperature. The frequency will lie within the channel 9 band from 35°C to 41°C but at other temperatures may not. The frequencies noted here were measured at an undefined room temperature: as one would expect, the carriers, therefore, are substantially below the nominal frequency.

SECTION 5

OPERATION AND CHECK OUT PROCEDURES

The instrument is completely sealed in hard epoxy and is not readily repairable, i.e. access to the internal components, wiring, or battery is not simple. There are four terminals accessible to the user; these are located in a slight depression and it is intended that when connection is made to the terminals, when about to implant the instrument, the depression would be leveled off with an RTV rubber.

Battery drain current may be measured by connection of an ammeter between the center two terminals; prior to sealing these two center terminals must be connected directly together.

After receipt of the r.f. carrier on a suitable radio and first demodulation, the two subcarriers may be separated and decoded. IRIG channel 9 is operative only over the approximately 35°C to 41°C; the subcarrier will be present over a much wider temperature range but will not fall in the IRIG channel 9 band allocation. IRIG channel 10 is modulated by the potential applied between the two outside terminals on the set of four described above; the subcarrier will be frequency modulated approximately 140 Hz for a 1 mV p-p signal within the 0.5 to 100 Hz pass band.

SECTION 6

RECOMMENDATIONS

There are eight areas which immediately came to mind as meriting consideration for further study or development. These are set out below with brief comments indicating proper justification and possible scope. These subjects are sufficiently involved with or close to the present program that, had time or funds been available, most of them would have been investigated in some detail.

1. Improved Remote Switch Access
2. Remote Switch with Zero Off Current Drain
3. General Circuit Simplification
4. Transmitting Antenna Study
5. Additional Channel Practicality
6. Rechargeable Power Source
7. Application of Advanced Packaging
8. Ultra Low Power Pressure Channel

6.1 IMPROVED REMOTE SWITCH ACCESS

A sharp burst of energy in the electromagnetic spectrum will be detected by the pickup coil of the remote power switch (L3, Fig. 13). If the level of this energy is great enough, e.g. a local lightning strike, the pulse will be conditioned by the two stage amplifier and will cause the bistable flip-flop to switch. A random, stray burst of noise may well meet the requirements for this trigger pulse; there were very occasional times in the laboratory, through the operation of a nearby faulty oven heater switch, that the remote switch circuit would be operated.

This situation may be remedied by means of a coded switching pulse. One might use a series of, say, three pulses at a given spacing, e.g. 1 KHz, to operate a trigger; or a signal modulated, continuously, at some given frequency, e.g. 1 KHz, could give access after a given time constant had been satisfied. Whatever the technique, and many present themselves, the remote switch could and, probably, should be given some noise immunity in future units.

6.2 REMOTE SWITCH WITH ZERO OFF CURRENT DRAIN

It was a design goal that the entire system have a drain amount of not more than 10μA in the OFF condition. The first switch built up had a drain of 20μA; this was subsequently reduced to about 12μA then 3μA. In the last case the trigger energy to which the switch would respond was enormously increased, it did not work well.

A different electronic approach has shown the feasibility of designing an electronic switch, operable from several feet distant, that will draw essentially zero current (<5 nA) in the OFF condition. It is suggested that such a switch might find broad application since the only competitive approach at the moment is a magnetic latching relay; the magnetic relay, however, is operable at only a few inches distant.

6.3 GENERAL CIRCUIT SIMPLIFICATION

Now that the system has been completed and its operation verified, a second look at each of the circuit solutions would be worthwhile. The objective of such a reappraisal would be general simplification and, as a consequence, reduced power consumption (longer operating life), and enhanced reliability.

6.4 TRANSMITTING ANTENNA STUDY

Most of the telemetry links established at present from chronic implantation sites in research animals are for relatively short ranges, e.g., 3 to 30 feet.

Much interesting experimental data has been obtained on this current program for antennae capable of operation at minimum power and capable of transmitting intermediate distances (half mile) in the VHF band. These results have been gathered together in the final report.

Various forages in the technical literature, which have failed to produce any information on antennae design applicable to our program need, indicated that a definitive program on this single subject would be valuable.

6.5 ADDITIONAL CHANNEL PRACTICALITY

In the original RFP, the possibility was raised of adding additional channels in the future. Relatively straightforward tests upon the existing developed circuitry would show how many extra channels could be incorporated and what penalties would have to be met in regard to size, weight, and powered lifetime.

As an estimate, with cognizance of the details of this instrument, at least three more channels could be added (to give a total of five) with no size increase, or weight penalty; current drain would be increased by about 250μA.

6.6 RECHARGEABLE POWER SOURCE

The need for a simple rechargeable battery is self-evident. Excellent batteries, such as nickel-cadmium or silver-cadmium, are available;

power level as great as 70 watts have been transferred without tissue damage through the intact skin[1, 2]. These three foregoing facts suggest that the time is opportune for a program to satisfy the stated need.

6.7 APPLICATION OF ADVANCED PACKAGING

The construction technique used in this instrument was soldered cordwood using discrete components (Fig. 24); hybrid, thick-film, integrated circuits, not sufficiently developed previously, have, as of this writing, the flexibility and quality to contain most of the subject circuitry. The advantages from such a move would be certain increased reliability, reduced power consumption, reduced instrument cost (incremental, excluding development), reduced volume (even with many additional channels).

6.8 ULTRA-LOW POWER PRESSURE CHANNEL

Incorporation of a pressure measurement channel into this instrument may not be done readily unless a disproportionate power drain is allocated for the transducer.

(A suitable pressure transducer would be the EOS Model 1015 with a 5000Ω bridge; such a transducer might draw greater than 1 mA from the battery.)

Addition of a pressure telemetering channel, compatible with the developmental philosophy in evidence thus far could prove a valuable research tool.

---

[1] Schuder, J. C., et al., "Energy Transfer into a Closed Chest by Means of Stationary Coupling Coils and a Portable High Power Oscillator", Trans. Amer. Soc. Artif. Int. Organs, Vol. VII, 1961.

[2] Dolan, A. M., et al., "Heat and Electromagnetic Energy Transport through Biological Material at Levels Relevant to the Intrathracic Artificial Heart", Trans. Amer, Soc. Artif. Int. Organs, Vol. XII, 1961.

APPENDIX I

PARTS LISTS

The Biopotential Amplifier:

Resistors	R101	2	Megohms	
	R102	2	"	
	R103	2	"	
	R104	2	"	1/8 W Allen Bradley
	R105	.47	"	
	R106	.47	"	±5% carbon composition
	R107	.02	"	
	R108	.02	"	
	R109	.22	"	
	R110	.56	"	
	R111	.22	"	
	R112	.56	"	
	R113	.1	"	
	R114	.47	"	
	R115	.47	"	
	R116	.1	"	
	R117	.1	"	
	R118	.56	"	
	R119	1	"	
	R120	Select, typ. 10 KΩ		
	R121	.22	Megohms	
Capacitors	C101	2.2 μF 4v electrolytic, Components Inc.		
Transistors	Q1, 2, 3, 4, 5, 6, 7, 9			D26E-5 General Electric.
	Q8			NS6065 National Semiconductor Corp.

The Biopotential Channel IRIG No. 10

Resistors	R201	.1	Megohms
	R202	.1	"
	R203	.39	"
	R204	.39	"
	R205	.1	"
	R206	.1	"
	R207	6.2	"
	R208	1	"
	R209	1	"
	R210	.68	"
	R211	.43	"
	R212	.24	"
	R213	.24	"
	R214	.12	"
	R215	.1	"
	R216	.27	"
Capacitors	C201	440	pF
	C202	440	"
	C203	220	"
	C204	100	"
	C205	220	"
	C206	100	"
Transistors	Q10, 11, 12, 13	D26E-5	
	Q14	NS6065	

Temperature Measurement Channel IRIG No. 9

Resistors	R301	.1	Megohms	
	R302	not used	"	
	R303	.1	"	
	R304	.47	"	
	R305	.47	"	
	R306	.1	"	
	R307	1	"	
	R308	6.2	"	
	R309	1	"	
	R310	1	"	
	R311	.68	"	
	R312	.43	"	
	R313	.13	"	
	R314	.13	"	
	R315	.62	"	
	R316	.1	"	
	R317	.27	"	
	R330	1.64	"	(series combination)
	R331	.51	"	typ.
	R332	65A6 Veco thermister		
	R333	.18	Megohms	
Capacitors	C301	330	pF	
	C302	330	"	
	C303	220	"	
	C304	270	"	
	C305	540	"	
	C306	270	"	
Transistors	Q20, 20, 22, 23	D26E-5		
	Q24, 25	NS 6065		

The Mixer, Driver and VHF Oscillator

Resistors	R401	1	Megohms
	R402	.82	"
	R403	.68	"
	R404	.43	"
	R405	1	"
	R406	1	"
	R407	.27	"
	R408	.22	"
	R409	.91	"
	R410	.22	"
	R450	3.3	Kohms
Capacitors	C401	820	pF
	C402	100	"
	C403	820	"
	C404	820	"
	C450	47	"
	C451	10	"
	C452	10	"
	C453	1000	"
Transistors	Q30, 31	D26E-5	
	Q32, 33	NS6065	
	Q40	NS9715	
Inductor	L1	10T	1/4 inch ID, 1/2 inch long, air core

Remote Power Switch

Resistors	R501	10	Megohms
(Megohms)	R502	.47	"
	R503	.12	"
	R504	5.6	"
	R505	1	"
	R506	5.6	"
	R507	5.6	"
	R508	5.6	"
	R509	1	"
	R510	1	"
	R511	.15	"
Capacitors	C501	1000	pF
	C502	1500	"
	C503	100	"
	C504	100	"
Diodes	CR1, 2, 3, 4,		IN4154
Transistors	Q50, 51, 52, 53, 54		D26E-5
	Q55		NS6065

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13. ABSTRACT

This document is the summation and final report of all work conducted on Air Force Contract Number AF 29(600)-5755. All research and development necessary for the fabricating of four chronically implantable instruments is described. The complete instrument comprises conditioning for low level biopotential signals, temperature sensing, two subcarrier oscillators (IRIG channels No. 9 and 10), a VHF transmitter using FM/FM multiplexing with a range of 1200 feet, a remote switch to activate the instrument and a saturated mercury battery of 500 mAH capacity. The VHF receiving station, including the antenna, was supplied as part of the program. Prime design goals were met such as transmitting range, and IRIG and FCC compatability; the design goal for power consumption was bettered by more than two times to give a powered lifetime of more than 30 days. Total program duration was 15 months.

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