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# A Passive Temperature Telemetry System

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# DESCRIPTION OF A PASSIVE TEMPERATURE TELEMETRY SYSTEM

by

R. E. Bobbett, A. R. Koelle, J. A. Landt, and S. W. Depp

## ABSTRACT

An electronic temperature-monitoring system is described. This system, designated Model 75, was designed and fabricated in 1975 to demonstrate the feasibility of monitoring the temperature of a bovine animal via a passively powered transponder implanted under the animal's skin. The purpose of this report is to document the functional elements comprising this successful preprototype system.

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## I. INTRODUCTION

The design and construction of the passive biotelemetry system described in this report was carried out at the Los Alamos Scientific Laboratory (LASL) operated by the University of California under contract to the Energy Research and Development Administration (ERDA). The work was inspired by the Animal and Plant Health Inspection Service (APHIS) branch of the US Department of Agriculture (USDA) and jointly funded by the USDA and ERDA.

The predecessor to this system, Model 73, was described in LASL report LA-6410-MS.[1] The Model 73 system successfully demonstrated the feasibility of passively powering a transponder in air at 1 GHz. Once powered, the transponder could transmit temperature and identification information by varying the backscatter cross section of the antenna, thus modulating the reflected rf carrier.

The Model 75 system was developed to determine the feasibility of subdermally implanting a transponder which could intercept sufficient rf signal to power its electronics and return data to the transmitter. The decision to transmit temperature data only was made jointly by USDA and LASL personnel in order to concentrate on solving the problems associated with implanted transponders. This decision simplified the hardware requirements for the transponder and receiver electronics without compromising the ultimate goal for the development of a subdermal electronic identification and temperature reporting transponder. This choice made it possible to demonstrate that passive (non-battery powered) transponders would operate under the skin without waiting for the development of a new digital encoding scheme. Limited funds required stepwise development.

The characteristics of the Model 75 system are as follows:

1. The system will read and display the temperature of a subdermally implanted transponder to within 0.1°C.
2. The data are considered to be valid only upon receipt of two consecutively identical temperature readings.
3. Signals from multiple transponders will not cause an error. Only the transponder with the strongest return signal will be accepted.
4. The transponder derives its power from the incident rf energy, that is, no battery is required in the transponder.
5. The transponder is encapsulated in a medical-grade elastomer for biological compatibility.
6. An rf source of 15 W at a frequency of 560 MHz will activate the implanted transponder

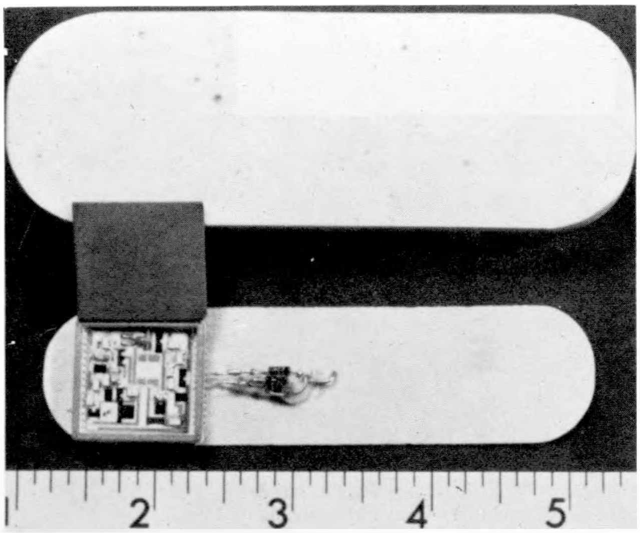


Fig. 1. Transponder.

at a maximum distance of 1 m. Increasing the output power increases the range.

7. The transponder has a potentially unlimited life.
8. Temperature can be read in less than 0.1 s.

## II. TRANSPONDER DESIGN

The purpose of the Model 75 system was to establish the feasibility of interrogating a passively powered transponder implanted under a bovine animal's skin. An implanted transponder would be protected from damage and loss. A passive transponder requires no periodic battery charging or replacement and contains no toxic materials. Figure 1 shows the transponder component parts before and after encapsulation. Figure 2 shows the construction of the transponder.

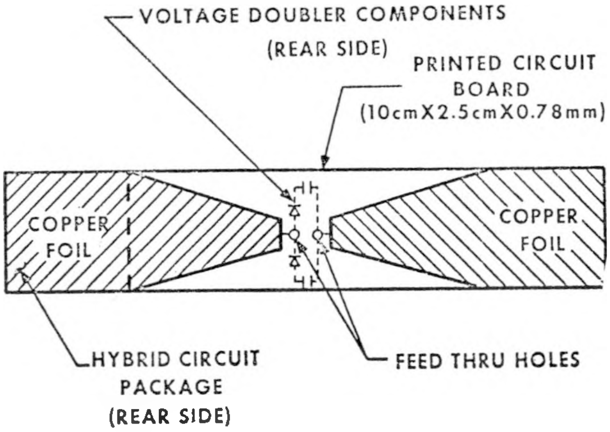


Fig. 2. Transponder construction.

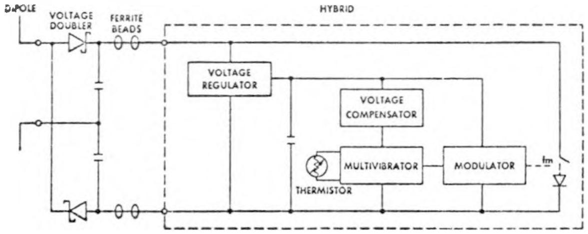


Fig. 3. Transponder block diagram.

The transponder was designed to be powered by a 15-W microwave beam at a distance of approximately 1 m from the animal. Therefore, the antenna design had to be capable of intercepting the power remaining after reflection and attenuation from and through the animal's skin to power the internal electronics. Additionally, the antenna had to reflect a modulating signal of sufficient amplitude to be detectable by the receiver.

Figure 3 is a block diagram of the transponder and Fig. 4 shows the electrical schematic. An incident rf carrier frequency is intercepted by the transponder antenna and rectified by the voltage doubler circuit. Since only the voltage doubler components need operate at high frequency, they are mounted externally to the hermetically sealed and rf-shielded hybrid package. These components are, however, glass encapsulated for protection from any potential body fluid intrusion. The dc voltage thus derived from the voltage doubler is regulated by a low-voltage drop regulator circuit to minimize voltage variations to the astable multivibrator circuit. A voltage compensation circuit for the multivibrator

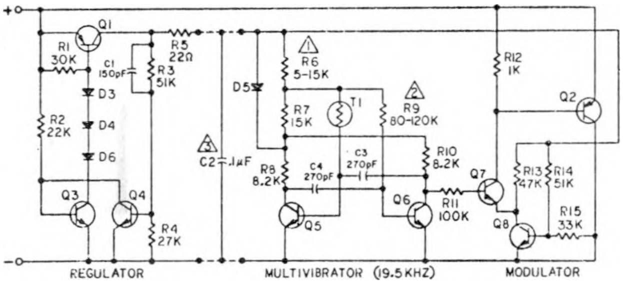


Fig. 4. Hybrid electrical schematic.

circuit further reduces the effects of any voltage fluctuations. A thermistor is utilized as one of the timing components in the multivibrator, thus the multivibrator frequency can be made proportional to the ambient temperature of the transponder. Components are selected and trimmed so that the proportionality is approximately linear over the animal's normal temperature range. The multivibrator frequency controls a modulator circuit that varies the loading on the rectifier and antenna. The variable loading on the antenna modulates the carrier frequency by changing the antenna backscatter cross section. A ratio of the loaded-to-unloaded backscatter cross sections, on the order of 10:1, allows for the interrogator electronics to optimally detect the modulation frequency.

Optimum operating frequency is influenced by antenna length, tissue conductivity and dielectric properties, antenna impedance when implanted, transponder voltage requirements, and depth of implant (Appendix). Calculations[2] over the frequency range of 100 MHz to 3000 MHz indicated that an optimum frequency would be near 560 MHz for an antenna length of 10 cm. Experimental data derived from tests in saline water confirmed that 560 MHz was near optimum for the antenna configuration shown in Fig. 2.

Final confirmation of the theoretical and saline water test data occurred on 23 September 1975 with the first implant. The transponder was cold-sterilized overnight in a solution of benzakonium chloride and then rinsed in a normal saline solution before implantation next to the backbone near the neck in a 1½-yr-old black steer (Fig. 5).

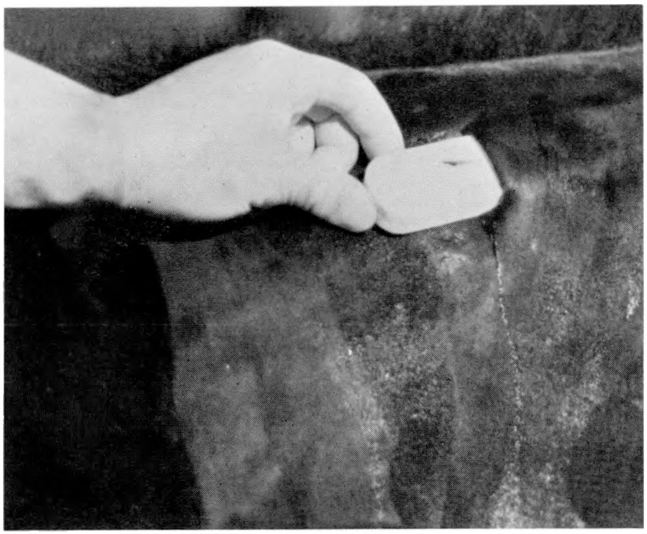


Fig. 5. Insertion of transponder.

Because of a broken wire, this unit was removed 13 November 1975 and replaced with a second transponder which has since operated for more than 1 yr with no evidence of animal rejection.

## III. INTERROGATOR-RECEIVER DESIGN

The interrogator receiver consists of an rf section for powering and interrogating the transponder in the uhf region of the electromagnetic spectrum and a receiver for processing the demodulated transponder signal derived in the rf section.

A uhf signal, generated by the rf source, is transmitted by an antenna in the direction of the implanted transponder. Approximately, 70% of the microwave beam reaching the animal is reflected by the animal's skin. The remainder of the beam penetrates the skin, is attenuated by the animal tissue, and finally reaches the transponder antenna. A portion of the signal is rectified for powering the transponder circuitry and a portion is reradiated back to the interrogating antenna. If sufficient incident signal exists for adequately powering the transponder, the reflected signal carries the transponder temperature data as a result of modulating the carrier at a frequency scaled to the transponder temperature. The interrogating antenna, which is also the transmitting antenna, intercepts the reflected signal for demodulation in the rf section. After demodulation the resultant signal is further processed in the receiver for presentation to a temperature display.

### A. rf Section

A block diagram of the rf subsystem is shown in Fig. 6. The cw output from the rf power source is routed through a coupler, where a low-level output is taken off for use as the local oscillator input to the two mixers. The rf power enters port 1 of a 3-port circulator and exits at port 2. From the circulator the rf power is directed to the transmitting antenna. This antenna also functions as the receiving antenna, picking up the modulated signal reflected from the transponder. The received signal enters the circulator at port 2 and exits at port 3. The modulated return signal is now available for further processing, having been separated from the cw transmitter signal.

The modulated return signal is then limited and attenuated to protect the mixers from excessive

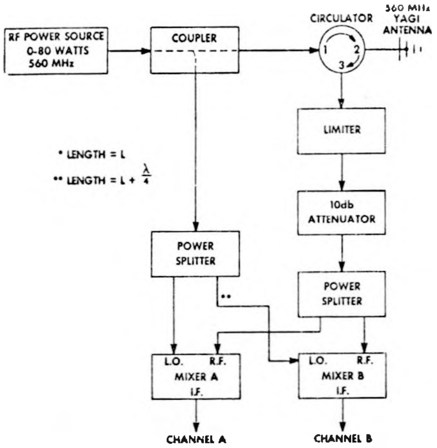


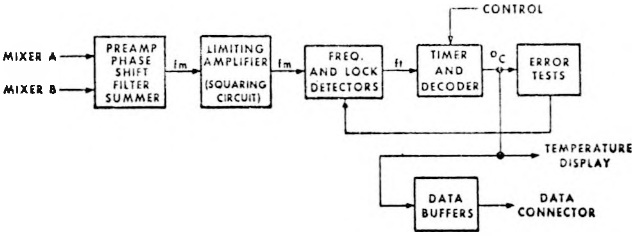
Fig. 6. rf section block diagram.

power levels, which could be obtained by reflection from large nearby objects.

The local oscillator and modulated return rf signals are each divided in power splitters to form the local oscillator and antenna inputs to mixers A and B. A net 90° phase shift is introduced between the local oscillator and antenna inputs to the two mixers so that both mixer outputs will not be at a null output condition simultaneously due to a quadrature phase condition between the local oscillator and antenna inputs. This phase relationship is a function of the round trip distance from the interrogator antenna to the transponder and back and therefore changes as the distance changes. If only a single mixer were used, the mixer output would drop to zero whenever the local oscillator and antenna inputs were in quadrature phase. With the arrangement shown, at least one of the two mixers will always avoid quadrature phase and therefore produce an output.[3] The mixer outputs are of the form of the modulation signal applied to the returned rf signal at the transponders and are either of the same phase or in phase opposition.

B. Receiver

The receiver block diagram is shown in Fig. 7. The two mixer outputs are first amplified in a low-noise preamplifier and then combined after a net 90° phase shift is introduced at the modulation frequency. The two mixer output signals are each replicas of the modulation signal introduced at the transponder, but they will vary in amplitude and polarity with changes in interrogator-to-transponder distance, one as a cosine function and the other as a sine function. The second phase shifting and summing operation can be shown to produce a single constant amplitude signal.[3]



NOTES:
1. MIXER INPUTS FROM RF UNIT
2. fm IS MODULATING FREQUENCY RECOVERED FROM MIXER SIGNALS
3. ft IS fm WHICH HAS BEEN SYNCHRONIZED TO DECODE TEMPERATURE.

Fig. 7. Receiver block diagram.

The combined signal is then amplified in a limiting amplifier, which converts the somewhat distorted, variable amplitude, nominally 20-kHz square-wave signal into a square wave of fixed amplitude. This signal is then sent to a phase-locked loop (PLL) which has the function of producing a cleaned-up signal at twice the modulation frequency. The desired temperature reading is proportional to this frequency.

The temperature reading is obtained in binary-coded decimal (BCD) form by counting cycles of the PLL voltage-controlled oscillator (VCO) by means of a BCD counter gated open by a 10-ms gate produced by a one shot. The reading is displayed if two such counts in succession result in the same number and if the PLL has not lost lock during the two 10-ms counting periods.

The receiver wiring diagram is shown in Fig. 8. Power and intermediate frequency (IF) signal inputs are received through connectors J1 and J2, respectively. Both of these connectors are mounted within an rf filter box wherein all connections between the connector and the card cage pass through feed-through capacitors. The temperature data are output via J3 and displayed on the front panel.

The electrical schematics for printed circuit boards (PCB) 1-6 are shown in Figs. 9-14, respectively. Power requirements were minimized by utilizing complementary metal-oxide semiconductor (CMOS) logic when appropriate.

The mixer IF outputs are amplified, phase shifted, and summed on PCB 1 (Fig. 9). A potentiometer,

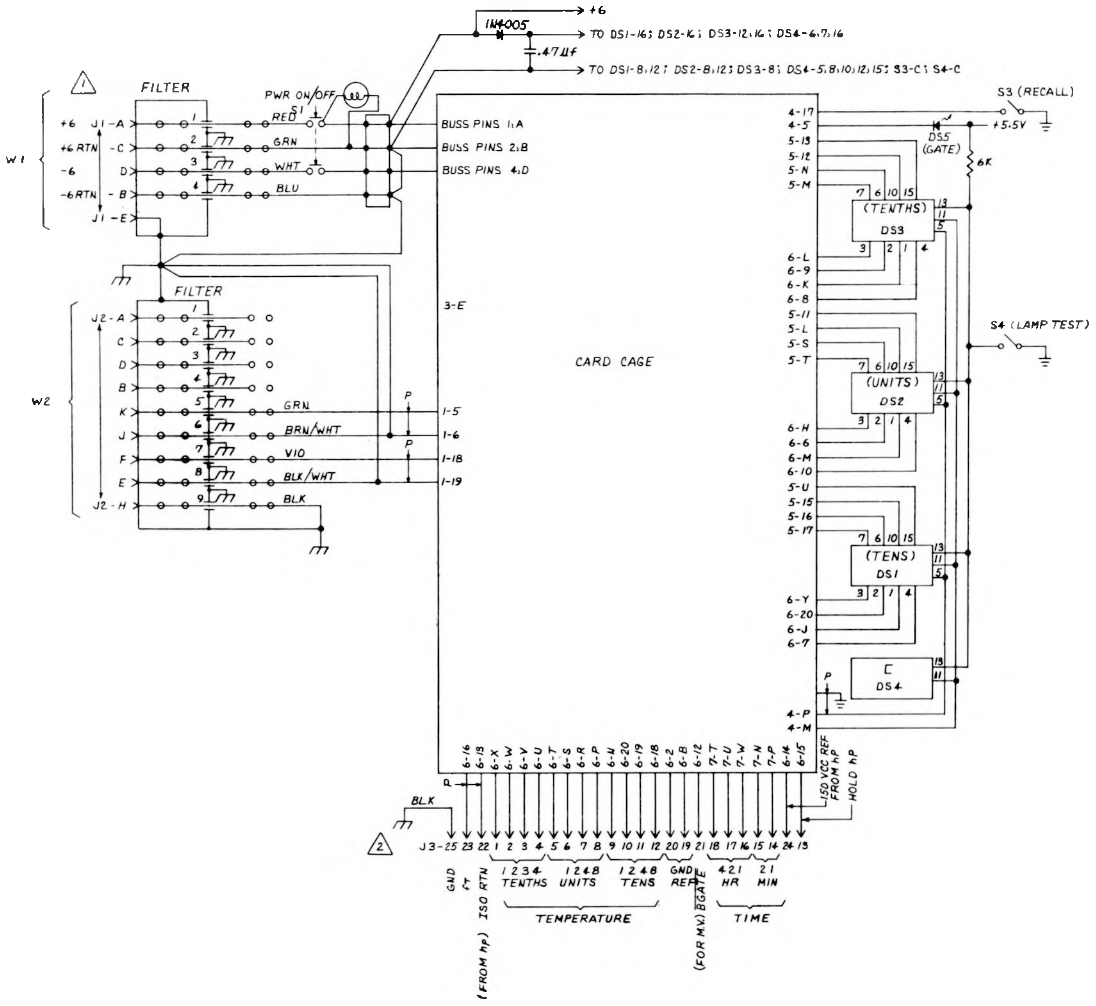


Fig. 8. Receiver wiring diagram.

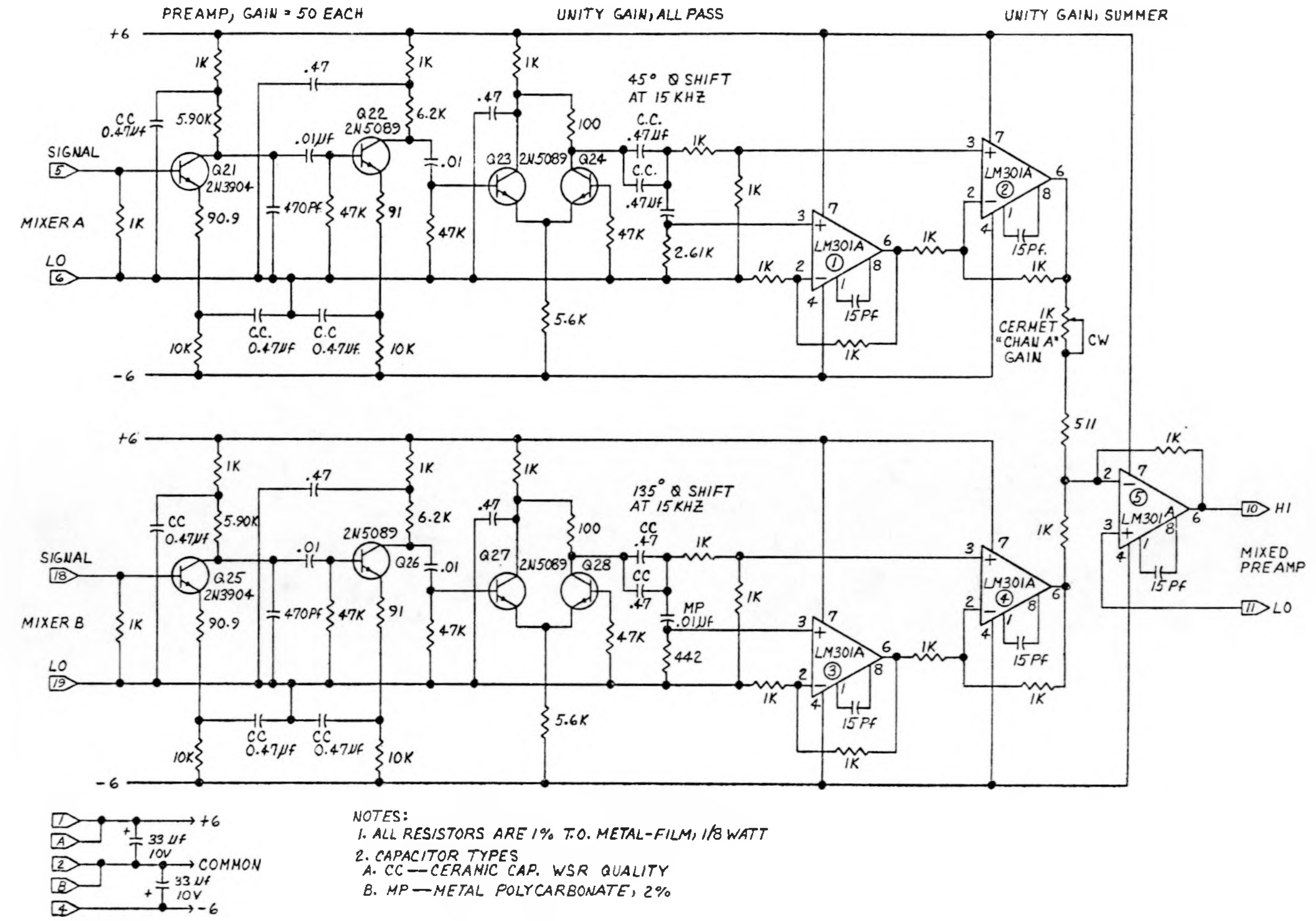
inserted in channel A just ahead of the summer, adjusts the gain of channel A so that it is approximately equal to that of channel B. The overall gain of the board is approximately 8 dB. The circuitry is designed to operate optimally at a center frequency of 15 kHz, which corresponds to a temperature of 30°C. The receiver operates optimally over a frequency band of 15 kHz, ±5 kHz, (30°C, ±10°C).

The summed output of PCB 1 is amplified and limited in PCB 2 (Fig. 10). The overall gain of this circuitry is approximately 114 dB.

The purpose of PCB 3 (Fig. 11) is to synchronize a PLL to the limited IF signal and thus generate a frequency that is equal to the modulation frequency of the transponder.

The PLL has a divide-by-2 circuit between the VCO output and comparator input to effectively multiply the input frequency by 2. The lock detector circuitry will generate an invalid signal if the PLL loses lock during a frequency measurement. The synchronizer circuitry ensures that the measurement period starts with a full cycle. The 555 timer is adjusted to enable the frequency counter for a measurement gate of exactly 10 ms. At the conclusion of the 10-ms measurement time, a WAIT signal of approximately 12 ms is generated to inhibit a new measurement, to enable the strobe generator on PCB 4 for processing the data, and to ignore any loss of lock during this time.

The frequency counter on PCB 4 (Fig. 12) counts the VCO output pulses for exactly 10 ms. Thus, for a frequency of 39.0 kHz, the counter will increment from zero (since it is initialized by the SYNC pulse from PCB 3 and at the conclusion of the previous



NOTES:
1. ALL RESISTORS ARE 1% T.O. METAL-FILM, 1/8 WATT
2. CAPACITOR TYPES
A. CC — CERAMIC CAP. WSR QUALITY
B. MP — METAL POLYCARBONATE, 2%

Fig. 9. Receiver PCB 1 schematic, preamp-summer.

reading) to 390. A fixed decimal point is placed between the last two digits yielding a temperature reading of 39.0°C. The strobe generator is enabled during the 12-ms wait period and generates a sequence of four pulses synchronized with the VCO frequency of the PLL. The first pulse, TEST, gates the comparator output of PCB 5. If the comparator output indicates an equality between word 1 and word 2, a LOAD signal is generated for updating the display memory, a 1.1-s retriggerable one shot is caused to generate various GATE signals to indicate a valid reading has been made, and a 5.5-s retriggerable one shot is caused to generate a signal which removes the BLANK signal from the display. The second generator pulse, XFER, updates the temperature storing register on PCB 5. The third pulse, RST, clears the frequency counter to initialize for the next reading. The fourth pulse, END, is returned to PCB 3 to be combined with the WAIT signal to stop the strobe generator.

The logic on PCB 5 (Fig. 13) compares the current reading in the frequency counter with the previous reading standing in the temporary temperature register. If the two values are equal, indicating two consecutively identical temperature readings were made, the W1 = W2 comparator output signal goes true.

The necessary buffering and isolation for interfacing the data and timing signals to an external data-acquisition device are provided by PCB 6 (Fig. 14).

## IV. RESULTS

The first passively powered, subdermally implanted transponder successfully met the requirements to telemeter the skin temperature of a steer at a distance of 1 m and 15 W of transmitted rf power. After about 24 h, the transponder temperature rose from an initial ambient air temperature to the animal's subdermal temperature. Interrogation of

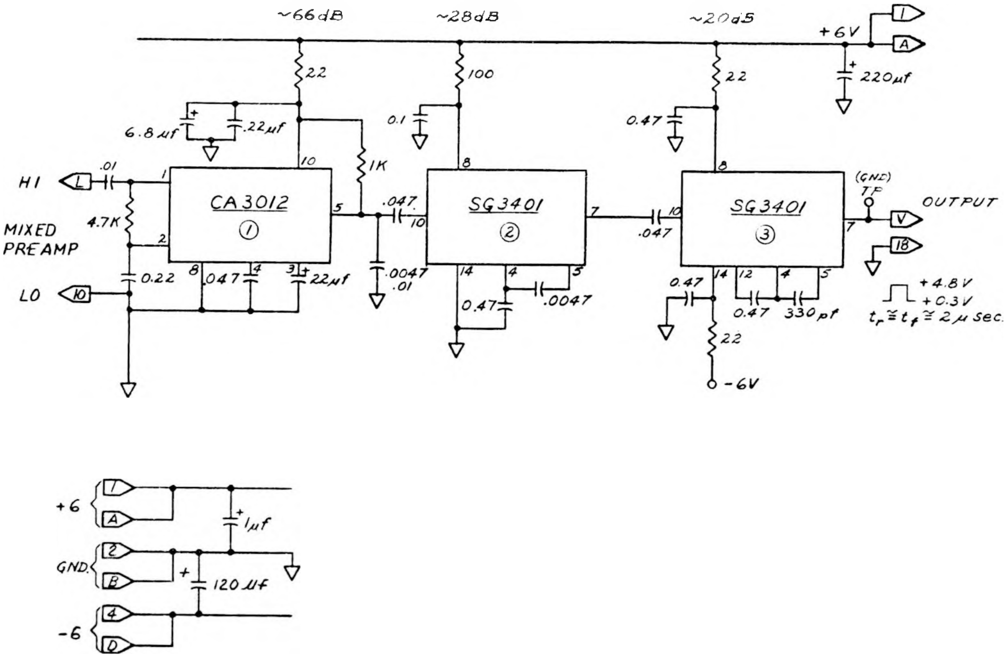


Fig. 10. Receiver PCB 2 schematic, limiting amplifier.

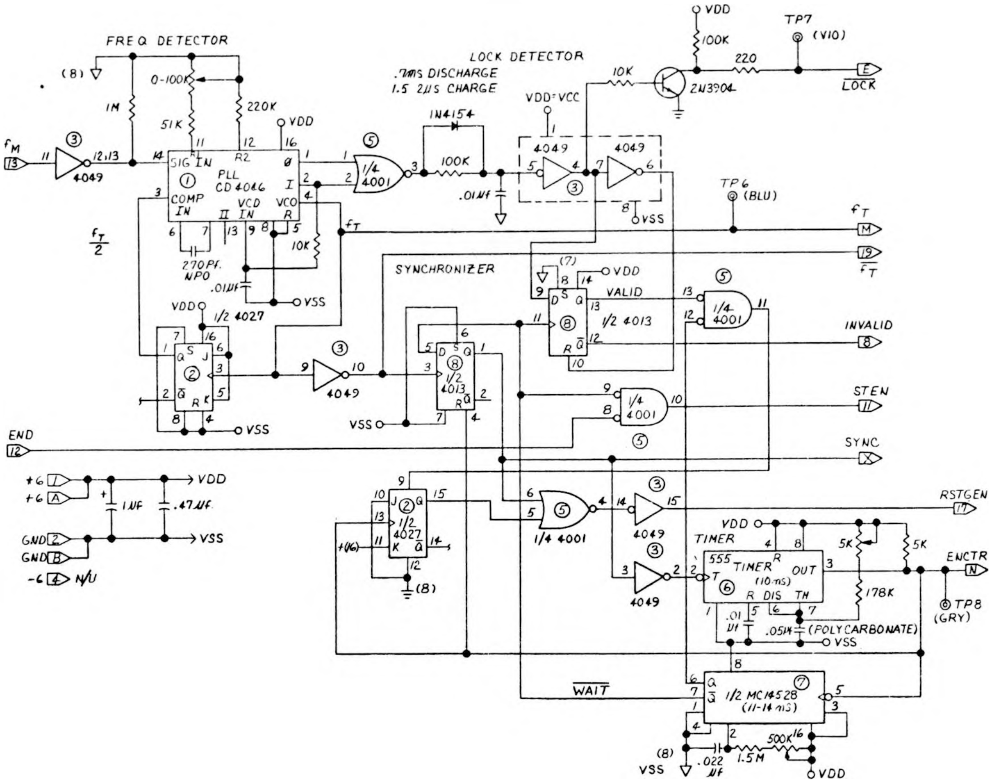


Fig. 11. Receiver PCB 3 schematic, PLL timer.

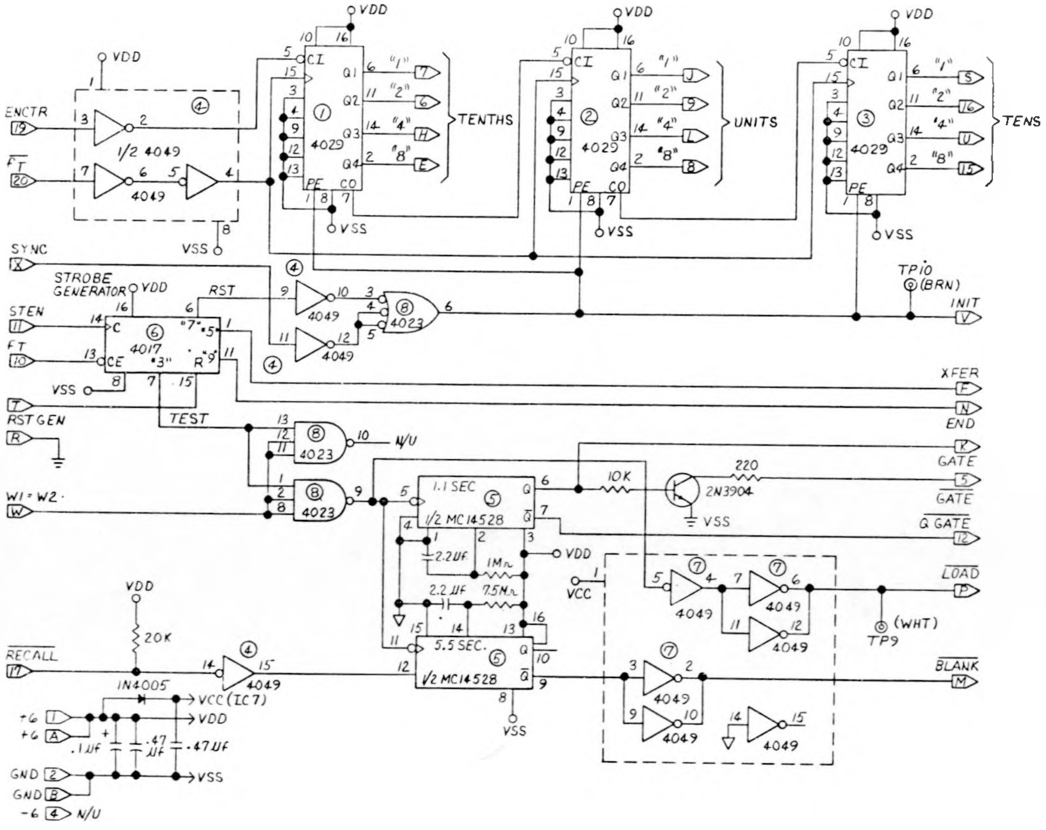


Fig. 12. Receiver PCB 4 schematic, frequency counter.

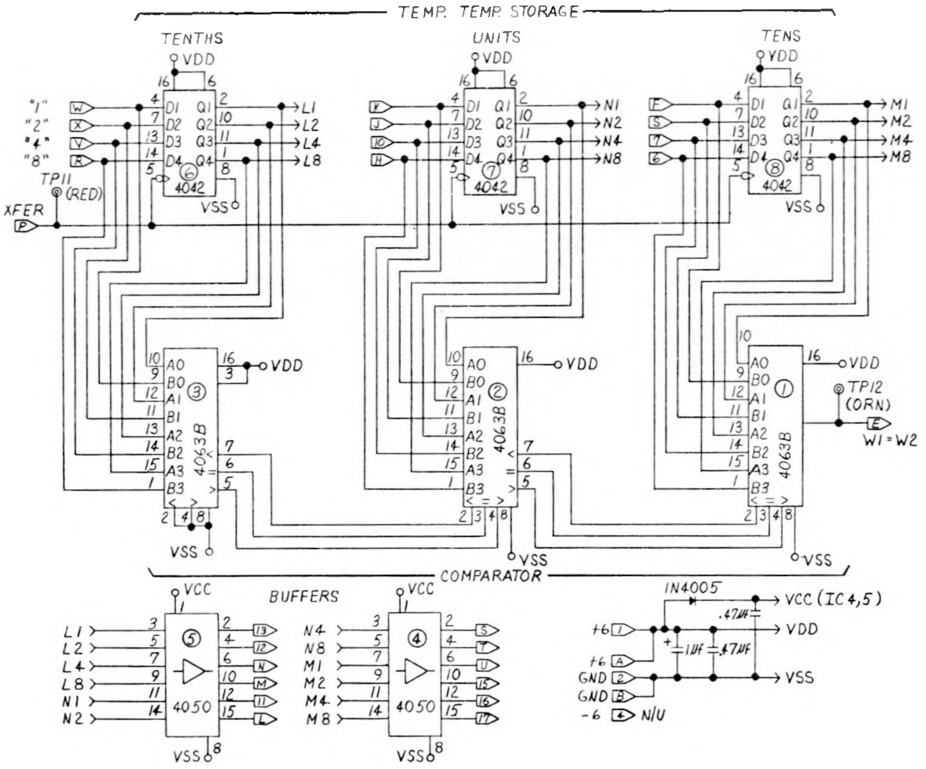


Fig. 13. Receiver PCB 5 schematic, storage comparator.

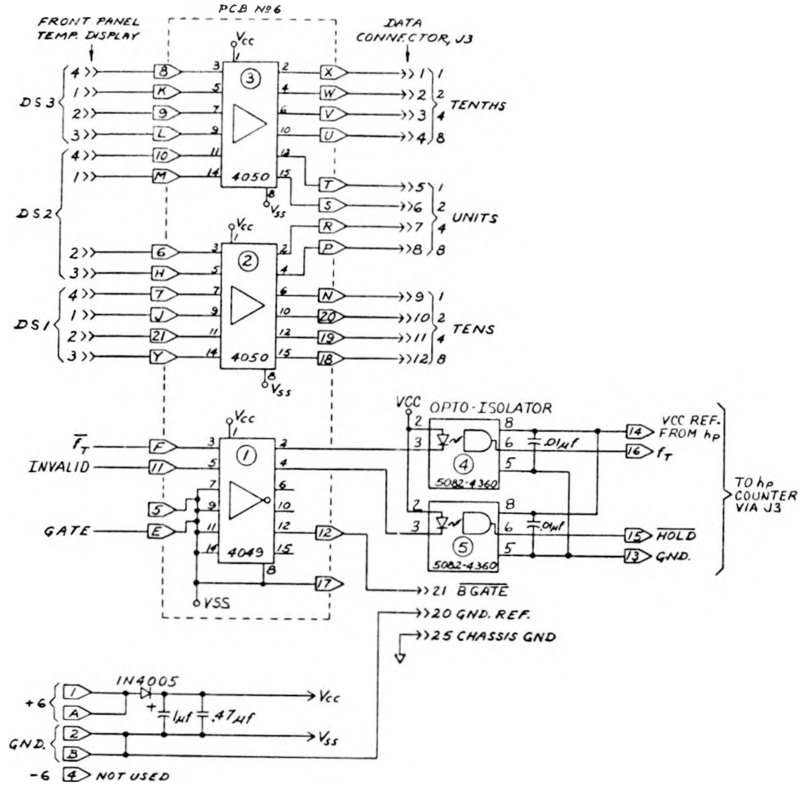


Fig. 14. Receiver PCB 6 schematic, data interface buffers.

the steer is shown in Fig. 15. The first transponder was removed after 3 wk because of intermittent operation caused by a broken wire between the voltage doubler circuit and the hybrid package. Construction of later transponders was modified to increase their reliability. In vivo tests conducted on the first implant showed that erroneous readings could occur when the transponder was losing power. This problem was remedied in later units by incorporating an electronic switch ahead of the modulator circuit that would effectively disconnect the modulator circuit from the multivibrator circuit when the operating voltage decreased to the multivibrator operating threshold voltage.

Visual examination of the transponder after removal from the steer indicated that the silicone elastomer coating was probably inert to body tissue (Fig. 16). This observation was later supported by an histologic examination of a fibrotic capsule that had formed around an implant removed from a steer at the Veterinary Services Laboratory (VSL) in Ames, IA.[4] The transponder had been implanted for 10 months.

Six transponders were implanted at the VSL in Ames, IA, by Dr. G. L. Seawright in December 1975. These units and the second transponder implanted by Dr. L. M. Holland at LASL in November 1975 have continued to operate for over 1 yr. Data taken from these units indicate that in addition to expected diurnal temperature fluctuations, stresses to the animal will cause a drop in skin temperature.[4,5]

## V. CONCLUSIONS AND FUTURE PLANS

The success of the Model 75 system has demonstrated that a passively powered transponder implanted under the skin of a steer within a medical-grade silicone elastomer is a viable approach to monitoring the animal's temperature. There is reason to believe that other physiological processes could also be monitored with the appropriate transducers and modifications to the system. During 1976 the Model 75 system discussed in this report was modified to enable the recognition of unique identification codes. Thus, in a computer-based system physiological data can be acquired along with source identification data independent of personal intervention.

The chief advantages of a biotelemetry system incorporating passively powered implantable transponders are that no batteries are required within the transponder and that the animal/patient need not be restrained.

## ACKNOWLEDGMENTS

The authors wish to acknowledge the services of J. C. Hensley, II, former Liaison Officer for USDA/LASL, and D. M. Holm, Liaison Officer for LASL/USDA, for their contributions toward defining system objectives and their efforts to obtain funding.

Dr. L. M. Holland and Dr. G. L. Seawright performed the implant operations at LASL and VSL, Ames, IA, respectively.

The technical services provided by Paul Salazar were critical to timely completion of project milestones.

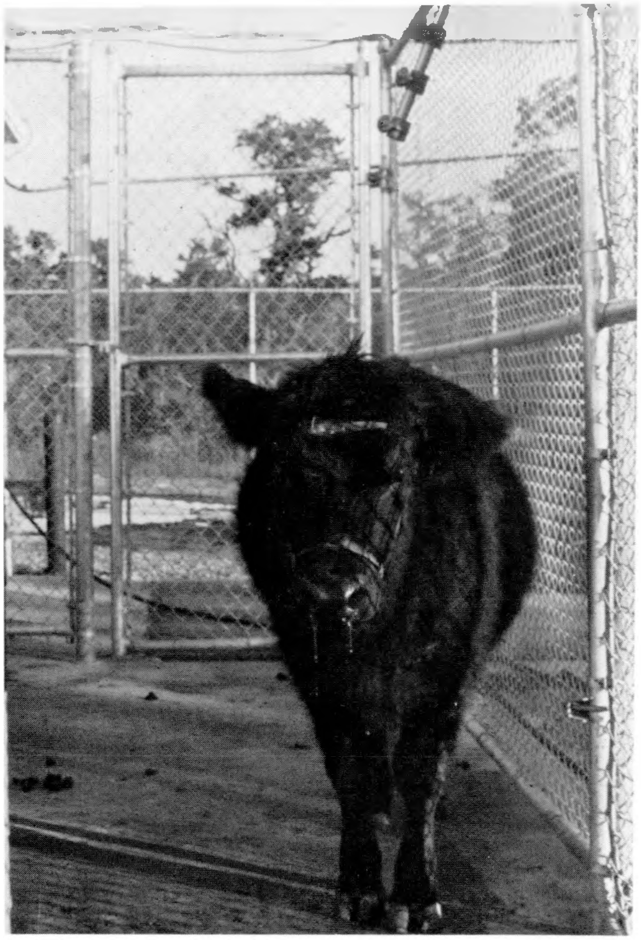


Fig. 15. In vivo interrogation of transponder.

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4. G. L. Seawright,** "Remote Temperature Monitoring in Animal Health Management," Proc. United States Animal Health Association Meeting, Miami Beach, FL, November 8-12, 1976.

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Fig. 16. Transponder encased within fibrous tissue.

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**Veterinary Services Laboratories, Ames, IA.

# APPENDIX

## SELECTION OF SYSTEM FREQUENCY

This appendix summarizes procedures used to predict system performance as a function of transmitter frequency. Included in the analysis are the effects of animal tissue, transponder antenna size, and the power requirement of the transponder electronics.

The problem was to select a frequency which would deliver sufficient power to the implanted transponder without requiring transmitted power to exceed biologically safe limits. The rf field available at the transponder antenna would be reduced by reflection from the air-skin interface and by attenuation through the animal's tissue.

The analysis and experiments were restricted to a frequency range of 100 MHz to 3 GHz. Signal directivity and antenna size are too large for frequencies below 100 MHz and rf attenuation through tissue is excessive for frequencies above 3 GHz. The electromagnetic skin depth for muscle tissue is about 30 mm at 100 MHz and decreases monotomically to 7 mm at 3 GHz. Consequently, approximating the animal as an infinite half-space is valid.

### PERFORMANCE REQUIREMENTS

Three factors were required for system operation. First, the transponder electronics were to be powered solely by the rectified rf signal that the transponder antenna received. This required that the transponder antenna deliver at least 1 V rms to a 150-Ω load. (The actual load is nonlinear and the 150-Ω value is an engineering approximation.)

Second, when the transponder antenna is short circuited sufficient signal must be scattered by the transponder antenna and received by the interrogator antenna compared to the unwanted signal reflected from the surface of the animal. Because of detection electronics, the reflected signal can be much less than the background noise. The signal scattered by the transponder antenna must produce at least 1 mV at the output of the rf section of the interrogator unit.

Third, the power scattered by the transponder antenna when loaded by 150 Ω must be at least 10 times less than that scattered under short-circuit conditions. This ratio allows detection of the signal in the presence of noise and undesired reflections and permits the interrogator to "lock on" to the desired transponder signal.

These three constraints are interwoven with transponder antenna design, tissue effects, interrogator antenna design, and distance from the interrogator antenna to the livestock animal. In the analysis which follows, it is shown that all constraints and safety guidelines are met using a frequency near 560 MHz.

### TISSUE EFFECTS FOR TRANSPONDER IN RECEIVING MODE

The biggest problems in the present design involve effects of animal tissue. Table A-I lists the properties of muscle tissue given by Schwan* and verified by others. The electrical properties of skin are similar to muscle.

The muscle tissue reduces the rf field available at the transponder antenna by reflection and attenuation. The transponder will be placed immediately under the skin, which varies from 3 to 5 mm in thickness. Figure A-1 summarizes the tissue effects, where the ratio of the field existing in the muscle to the incident field is plotted as a function of depth and frequency. These curves indicate that minimum losses (curve maxima) are incurred around 1.5 GHz.

TABLE A-I

MUSCLE TISSUE PROPERTIES

| f (MHz) | $\varepsilon_r$ | Conductivity (mho/m) |
|---|---|---|
| 100 | 70 | 0.77 |
| 200 | 56 | 1.0 |
| 400 | 53 | 1.1 |
| 700 | 52 | 1.3 |
| 1000 | 50 | 1.3 |
| 3000 | 46 | 2.2 |

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*Schwan, Herman P., "Electrical Characteristics of Tissues," Biophysik 1, pp. 198-208, 1963.

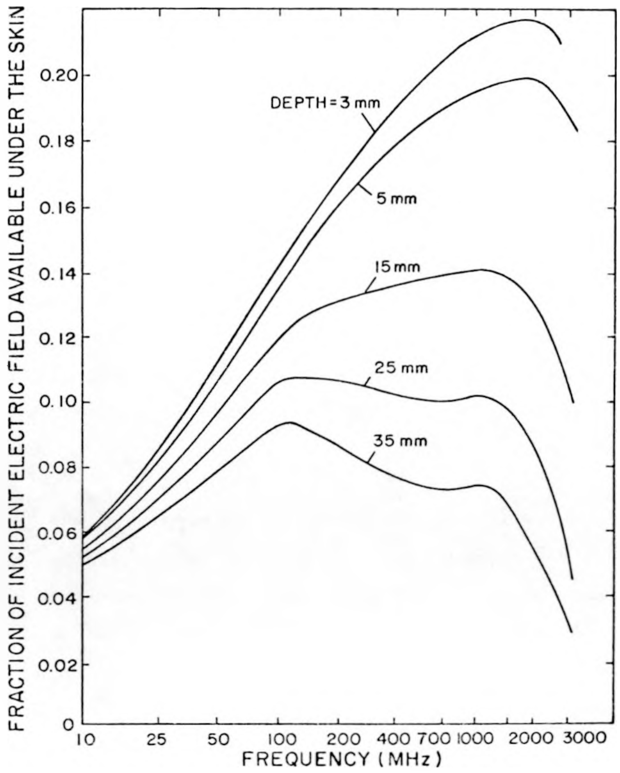

Fig. A-1. Fraction of subdermal incident field vs frequency and depth.

TRANSPONDER ANTENNA CHARACTERISTICS IN RECEIVING MODE

An equivalent circuit for transponder antenna and load is one in which the antenna is the voltage source $V_A$ with a source impedance $Z_A$ driving a load impedance $Z_L$. The voltage source is equal to the product of the effective antenna height $h_e$ and the field strength E. Both $h_e$ and $Z_A$ are affected by antenna design and the medium in which the antenna is immersed.

Roughly, $h_e$ is proportional to the physical length of the antenna and $Z_A$ is minimum when the antenna is resonant. To maximize the load voltage $V_L$ the antenna should be made as long as possible ($V_L \alpha \ell E Z_L / Z_A + Z_L$). The upper limit on size from other considerations is 10 to 15 cm. A 10-cm dipole, placed under the skin near the air-skin interface, will resonate between 550 and 600 MHz. Consequently operation near this frequency will optimize antenna performance and the losses suffered from tissue effects at 550 to 600 MHz are only 5% more than optimum (that of 1.5 GHz). Operation of the 10-cm dipole near the interface is summarized in Figs. A-2 and A-3. Figure A-2 displays antenna performance by plotting the ratio of $V_L/E_I$ vs frequency, where $V_L$ is the load voltage and $E_I$ is the field strength at the antenna location. Figure A-3 shows the overall performance by plotting $V_L/E_I$ vs frequency, which includes medium effects as well as effects of $h_e$, $Z_A$, and $Z_L$. Optimum performance is near 600 MHz for the dipole.

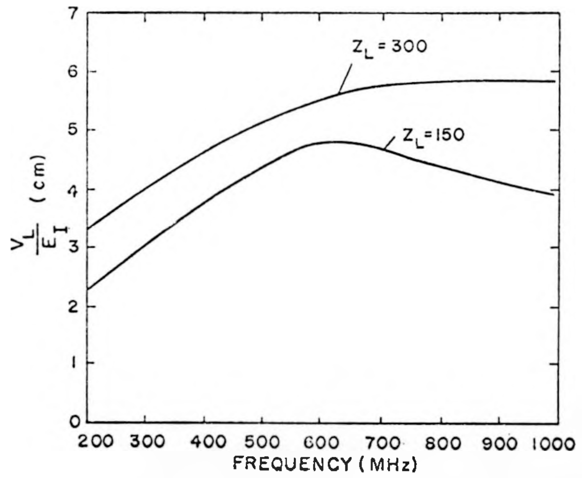

Fig. A-2. Ratio of load voltage to incident field vs frequency and load impedance, without inclusion of medium effects.

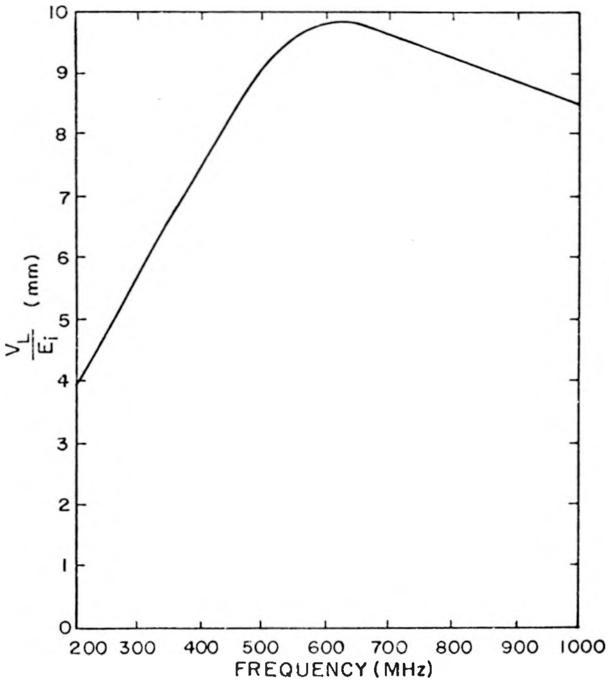

Fig. A-3. Ratio of load voltage to incident fields vs frequency, includes medium effects.

These theoretical predictions are confirmed qualitatively by the measurements plotted in Fig. A-4 of an actual suitable antenna. This antenna is similar to the 10-cm dipole but with "paddles" placed over the ends to provide a housing for the transponder electronics package. The best performance is obtained between 550 and 660 MHz and the dipole response closely approximates that of the actual antenna.

## TRANSPONDER ANTENNA CHARACTERISTICS IN THE SCATTERING MODE

The scattering properties of an antenna can be displayed in terms of a backscatter cross section as shown in Fig. A-5 for the 10-cm dipole immersed in muscle tissue near the air-skin interface. Figure A-5 displays the cross section in terms of the incident field that exists at the dipole location, and thus does not include the effects of the interface or propagation attenuation of the incident or scattered signals.

Between 550 and 600 MHz, the backscatter cross section is approximately 100 $cm^2$ under short-circuit conditions. Using this value and including reflection and propagation losses and tracing the signal through the rf circuitry of the interrogator unit, a signal of approximately 2 mV is obtained.

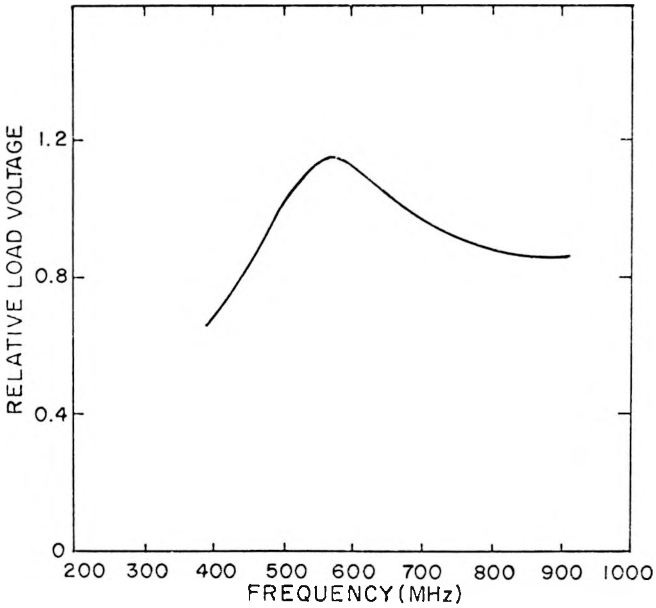

Fig. A-4. Measured load voltage vs frequency of "paddle" type dipole.

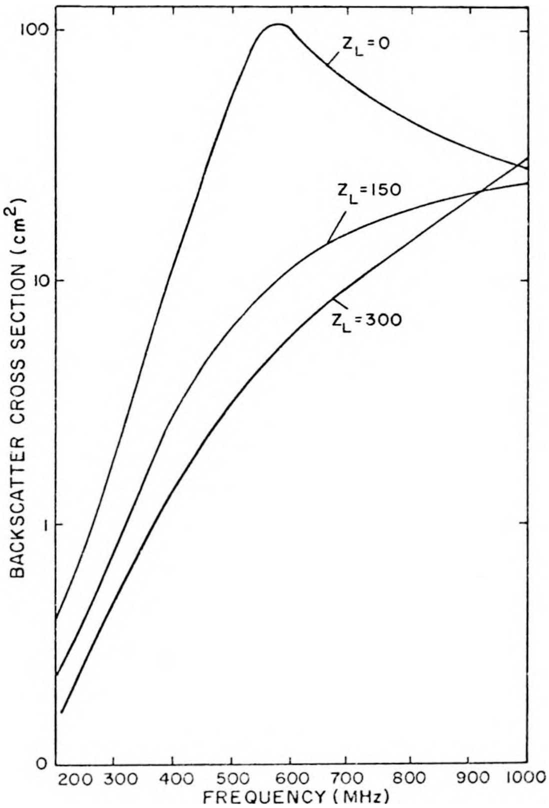

Fig. A-5. Backscatter cross section vs frequency and load of implanted dipole.

Figure A-5 also shows that operation is less favorable at other frequencies because loading has only a minor effect on backscatter cross section. This is undesirable since, with the present system, performance depends on changes in backscatter cross section with loading.

## SUMMARY

With the given constraints of size, tissue effects, and transponder voltage requirements, optimum system performance is near 560 MHz.

The operating range can be increased by increasing the voltage available to the transponder, decreasing the transponder voltage requirement, or by a combination of both. Voltage available to the transponder may potentially be increased by increasing the rf output power (this may require pulsing to keep the average energy level below the safety limit of 1 $MWh/cm^2$), improving the effective load impedance (by matching and/or pulsing the rf signal), decreasing the rf frequency (increasing the antenna's resonant length), and decreasing losses through the rectifier. A decrease in the voltage requirements can be accomplished by utilizing low-voltage components. All of these alternatives will be studied during the next stage of this program.

The transponder in this system (Model 75) can be activated by an incident microwave power density which is only 16% of the biological safety guidelines.

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