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A Completely Implantable Three Channel Temperature Biotelemetry System*

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ABSTRACT

A completely implantable three channel pulse modulated transmitter and corresponding external receiver has been developed to telemeter, from free ranging animals, body temperature and internal temperatures of an intracorporeal radioisotope heat source cooled by flowing blood. Temperatures ranging from 4 to 80° C can be telemetered over a range of 4 meters. Life expectancy of the device exceeds 10 months with calibration accuracy maintained to within 0.2° C.

INTRODUCTION

Over the past six years this laboratory has been conducting research on the long-term physiologic effects of added endogenous heat in the miniature swine, relative to the artificial heart program(1). Electrical heaters were implanted in the porcine thoracic aorta, using circulating blood as a coolant, with heater power inputs of up to 80 watts or more. Heater power input and temperature transducer output were measured via percutaneous leads, a source of continuous problems due primarily to subcutaneous breakage. In the current program(2), heat is supplied by a 50-watt radioisotope heat source, thus eliminating percutaneous power leads. To obtain internal temperature measurements without introducing percutaneous leads, a three channel temperature telemetry system was designed and fabricated which transmits, over distances up to 4 meters, temperature data related to the heat exchanger.

DISCUSSION

Design Considerations

In the present heat exchanger design, temperatures are sensed by thermistors at the heat source-heat exchanger interface, the blood-heat exchanger interface and the body tissue-heat exchanger interface. The telemeter system had to accomodate transmission of these three temperatures from each of six animals in the same room, and if separate transmitters were used for each measurement, identification of the 18 separate measurements would necessitate very stable transmission frequencies, a requirement which would unduly complicate each transmitter. Thus a multi-channel telemeter was necessary, preferably with a transmission frequency in the range of 88 to 108 MHZ to allow the use of standard FM receivers.

Past experiments have demonstrated numerous cases of eventual failure of the heat exchanger and death of the animal due to reduction or cessation of blood flow through the exchanger as a result of slow thrombus formation near the junctions of aorta and heat exchanger blood tube. This phenomenon may be detectible prior to animal death by monitoring the increase in interface temperature between the exchanger wall and the blood as flow is reduced. Since this situation is slow to develop, however, it is necessary that the life of the temperature telemeter be at least 6 months. The circuit to be described satisfies this specification without resort to transcutaneous power transmission or remote switching techniques.

Prior to implantation of the heat exchange, the temperature of the exchanger blood tube wall must be maintained below 55 °C to minimize damage to the blood and prevent breakdown of the anticoagulent coating deposited on the tube wall. The wall temperature would rapidly exceed this maximum temperature if the heat exchanger were stored in air. Consequently, the entire heat exchanger and incorporated telemetry package is placed in a cooling bath(2) at 4 °C. This low temperature extreme allows sufficient time for transfer in air from the bath to the surgical site before the wall temperature climbs beyond the allowable 55 °C. Once implanted, the maximum monitored temperature will be about 80 °C at the interface between the heat source and exchanger. The temperature telemeter thus must tolerate rapid temperature excursions and, for the purposes of studying transient and steady state heat transfer phenomena, maintain calibration during and following such excursions.

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DISCLAIMER

Telemeter Circuit Description

A block diagram of the telemetry transmitter is shown in Figure 1, and a complete circuit diagram is given in Figure 3. The circuit consists of an astable multivibrator triggering the first of three monostable multivibrators, each of which triggers the next in succession. The on-time of the first monostable (that time during which transistor Q1 is not conducting) is dependent on the time constant RC, where R in this case is a 1 megohm thermistor*; the other monostables operate similarly. The equation for on-time T is easily shown to be:

$$T = RC \ln \left[\frac{2V_{cc} - V_{S2} - V_{BE(SAT)}}{V_{cc} - V_{BE(ON)}} \right]$$

For the circuit elements used in this case,

$V_{cc} = 1.35$ volts (battery voltage),
$V_{S2} = 0.42$ volts (voltage from point P to ground. See Figure 3).
$V_{BE(SAT)} = 0.52$ volts (voltage from base to emitter of saturated transistor),
$V_{BE(ON)} = 0.45$ volts (voltage from base to emitter required to turn on transistor).

Choosing C = 0.01 μf, T will equal 4 msec at body temperature (about 38° C) and will range from about 0.3 to 20 msec over the temperature range anticipated (4 to 80° C). The period of the astable multivibrator is about 65 msec, much longer than the sum of the longest on-times of the monostables, allowing its use in the receiver as an identification (ID) pulse to identify and associate each temperature-dependent pulse with its respective thermistor. The wave-forms at the output of the astable and each monostable, taken at the collector of transistor Q1, are shown in Figure 6.

The output of monostables one and three are used to turn on the gating circuit which in turn activates the transmitter+, a monolithic integrated circuit tunable over the standard FM band (88-108 MHZ). Thus the transmitter is on only during the period of the temperature-dependent pulses T_1 and T_3 (see Figure 6), a time which at normal operating temperatures is less than 7% of the total cycle as determined by the period of the astable multivibrator. Because of this, although the operating current drain of the transmitter alone is 450 microamperes, the average current drain of the entire telemeter is only 122 microamperes. When powered by three parallel mercury type cells with a capacity of 600 ma-hr, the telemeter can be expected to transmit data for a period exceeding 10 months. This figure includes a 100% safety factor to compensate for the fact that this type of cell will not deliver full rated capacity when under light load.

The complete telemetry package, ready for potting in the heat exchanger, is shown in Figure 5.

Receiver Circuit Description

A block diagram of the telemetry receiver is shown in Figure 2 and a complete circuit diagram of the receiver circuit is given in Figure 4. To avoid the necessity of constructing a signal detection receiver, a commercial FM receiver* was used, though in this application the receiver must only detect the presence or absence of the FM center frequency. A square pulse signal with considerable superimposed noise appears across the FM amplitude variation damping capacitor (C424) of the FM ratio detector circuit of this receiver (see Figure 4). This signal is amplified by a common-emitter amplifier, an addition to the FM receiver, and transmitted by cable to the Pulse Detection-Separation (PDS) network.

Typical waveforms showing the processing of the signal in the PDS network are shown in Figure 7. Processing of the signal (Figure 7b) begins in the Pulse Height Discriminator (PHD) consisting of a Schmitt trigger adjusted to have maximum hysteresis, assuring that the Schmitt will not change its output state unless changes in the input signal are of maximum excursion. The PHD eliminates nearly all of the superimposed noise since this noise is rarely of maximum excursion (Figure 7c).

The output of the PHD is fed into the ID Pulse Recognition Circuit (PRC) as well as the Pulse Separation Circuit (PSC). The first of these two circuits consists of a unijunction delay timer which is reset by the leading edge of any positive pulse from the PHD. If a positive pulse does not occur for a length of time equal to the minimum possible ID pulse duration (Figure 7c), the unijunction circuit will not be reset before it times out, thus providing a small spike pulse (Figure 7d) just prior to the end of the ID pulse. This spike pulse is used to reset the PSC as explained below.

The PSC is comprised of J-K flip-flops and nor-gate logic, designed to separate the pulses T_1, T_2, and T_3 into channels 1, 2 and 3, respectively (Figure 6, 7). Output from a single channel can be selected by a rotary switch at the output of the PSC. The spike pulse from the PRC resets the PSC logic just prior to the pulse T_1, assuring that the output of channel 1 will truly be pulse T_1, the output of channel 2 will be pulse T_2, and so on. Note that the lack of transmitter signal between pulse T_1 and pulse T_3 is interpreted by the receiver to be pulse T_2.

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* Type 6A61J1, Fenwall Electronics, Inc. Famingham, Mass.

\+ Model M-5, Belair Electronic Laboratories, Bowie, MD 20715.

* Model GR-43A, Heath Company, Benton Harbor, Michigan.

The signal from the selected channel is fed into the Counter Control Circuit. The output of this circuit consists of two 4-microsecond trigger pulses which control the digital counter*. The first is a rest command pulse which occurs at the leading edge of input pulse (T_1, T_2 or T_3) and the second is an inhibit count command pulse which occurs at the trailing edge of the input pulse. The output of a 100 KHZ crystal oscillator** is counted by the digital counter during the time between the rest command and inhibit command, thus measuring the period of the input pulse. The magnitude of this period is inversely related to the temperature of the corresponding thermistor in the telemeter circuit.

Calibration and Stability

The entire system is calibrated over a range of 4-80° C by immersion of each thermistor in a water bath of known temperature and recording the corresponding pulse period from the receiver counter. Time stability of calibration was determined by bench testing; over a two-month test period the drift of any channel was less than + 0.17, -0.0° C.

Since the temperature sensing units are remote to the telemeter package it is possible for changes in temperature ambient to the package to cause calibration changes. However, the package is contained within the animal's body, limiting such ambient changes to no more than about 3° C under ordinary conditions. Bench tests have shown that an ambient temperature change from 38 to 43.5° C will cause a calibration change of less than 0.06° C. Such precision is required only following implantation, so that larger calibration shifts during the 4° C ambient period in the pre-implantation coolant bath are not critical.

The problem of calibration drifts due to long-term decreases in battery voltage (affecting on-time of the monostables) was avoided by the inclusion of the 1N4149 diode and parallel 22,000 ohm resistor in the collector circuit of transistor Q2 in each monostable. This raises the effective saturation voltage of Q2 from 0.06 volts to about 0.42 volts with results of relative insensitivity of monostable on-time to supply voltage changes (less than 1% change for battery voltage changes of from 1.1 to 1.6 volts) (3).

CONCLUSIONS

Long-term bench evaluation and preliminary in vivo trials in actual miniature swine preparations have indicated that this telemeter system performs as intended. It may be noted that, with a corresponding decrease in battery lifetime, the design is amenable to expansion for applications requiring additional channels of temperature data, still using but a single carrier without multiplexing. Physiologic information other than temperature could conceivably be transmitted in like manner by suitable conditioning of any transducer output. Frequency modulation of the carrier could provide yet another channel of information with few or no additions to the transmitter; however, the receiver would require substantial additions.

REFERENCES

(1) See the First, Second, Third, Fourth and Fifth Twelve-Month Technical Progress Reports on a Study on the Effects of Additional Endogenous Heat Relating to the Artifical Heart; Pacific Northwest Laboratory, Richland, Washington. To the National Heart and Lung Institute, Bethesda, Maryland; available through the Clearinghouse for Scientific and Technical Information, Springfield, Virginia. 1967-1971.

(2) Gillis, M. F., Decker, J. R., et al., Technical Progress Report: Biological Effects of Intracorporeal Radioisotope Heat Sources, Richland, Washington; to the Division of Biology and Medicine, U. S. Atomic Energy Commission. In progress.

(3) Pauley, J. D., Shirer, H. W., Pippitt, D. D., "A Simple Pulsed Transmitter for Telemetering Body Temperature from Free Ranging Animals", Proceeding of the IEEE - National Telemetering Conference, Houston, 1968, p. 386-90.

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* Model DM-5000, Technology/Versatronics, Inc. Yellow Springs, Ohio.

** Model L14C Connor-Winfield Corp. Winfield, Il. 60190.

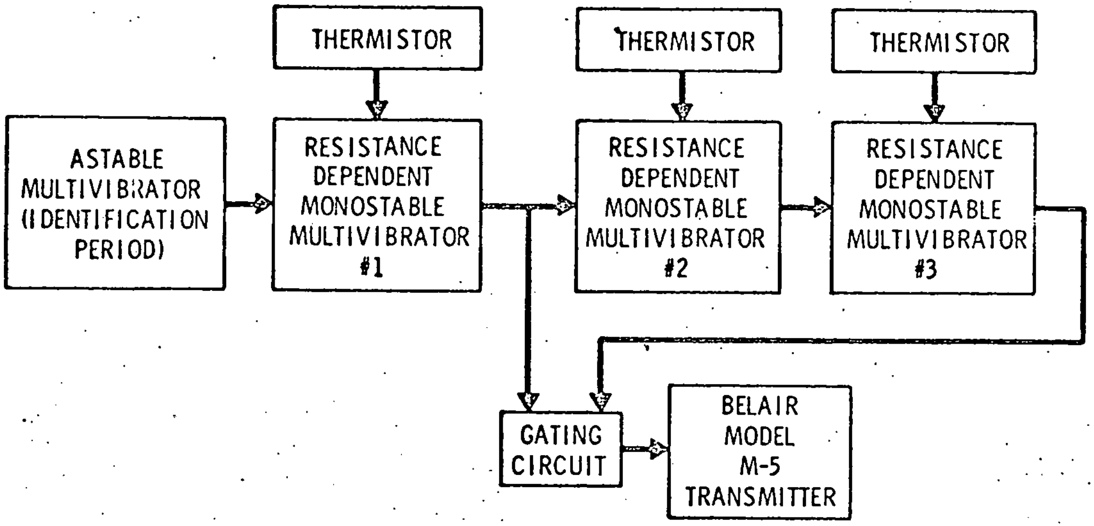


Figure 1. Block diagram of three-channel temperature telemetry transmitter.

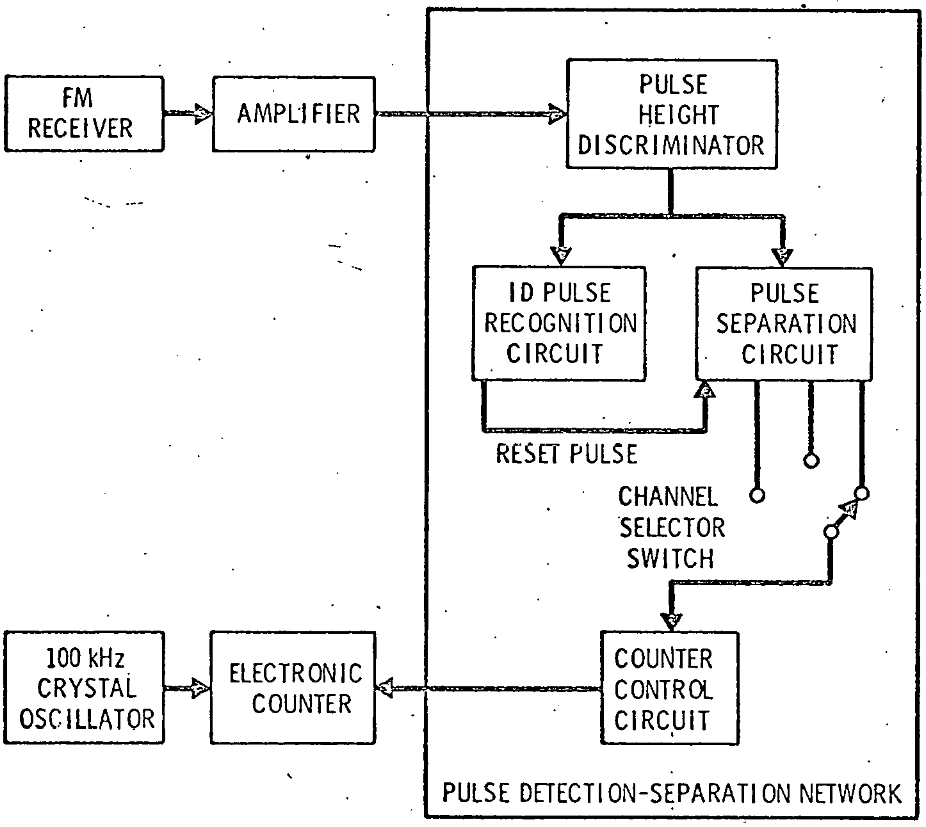
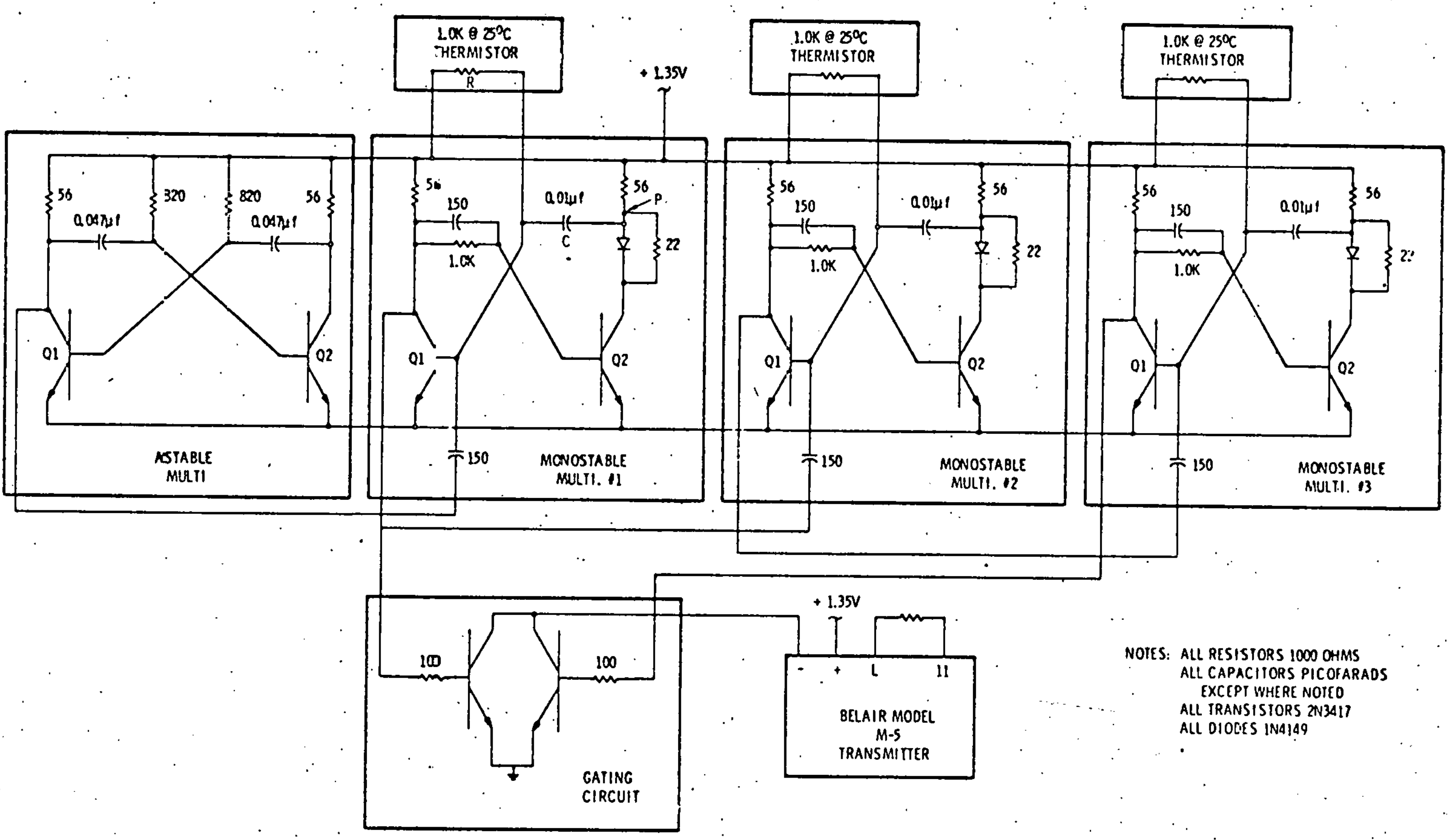


Figure 2. Block diagram of three-channel temperature telemetry receiver.



NOTES: ALL RESISTORS 1000 OHMS
ALL CAPACITORS PICOFARADS
EXCEPT WHERE NOTED
ALL TRANSISTORS 2N3417
ALL DIODES 1N4149

Figure 3. Circuit diagram of three-channel temperature transmitter.

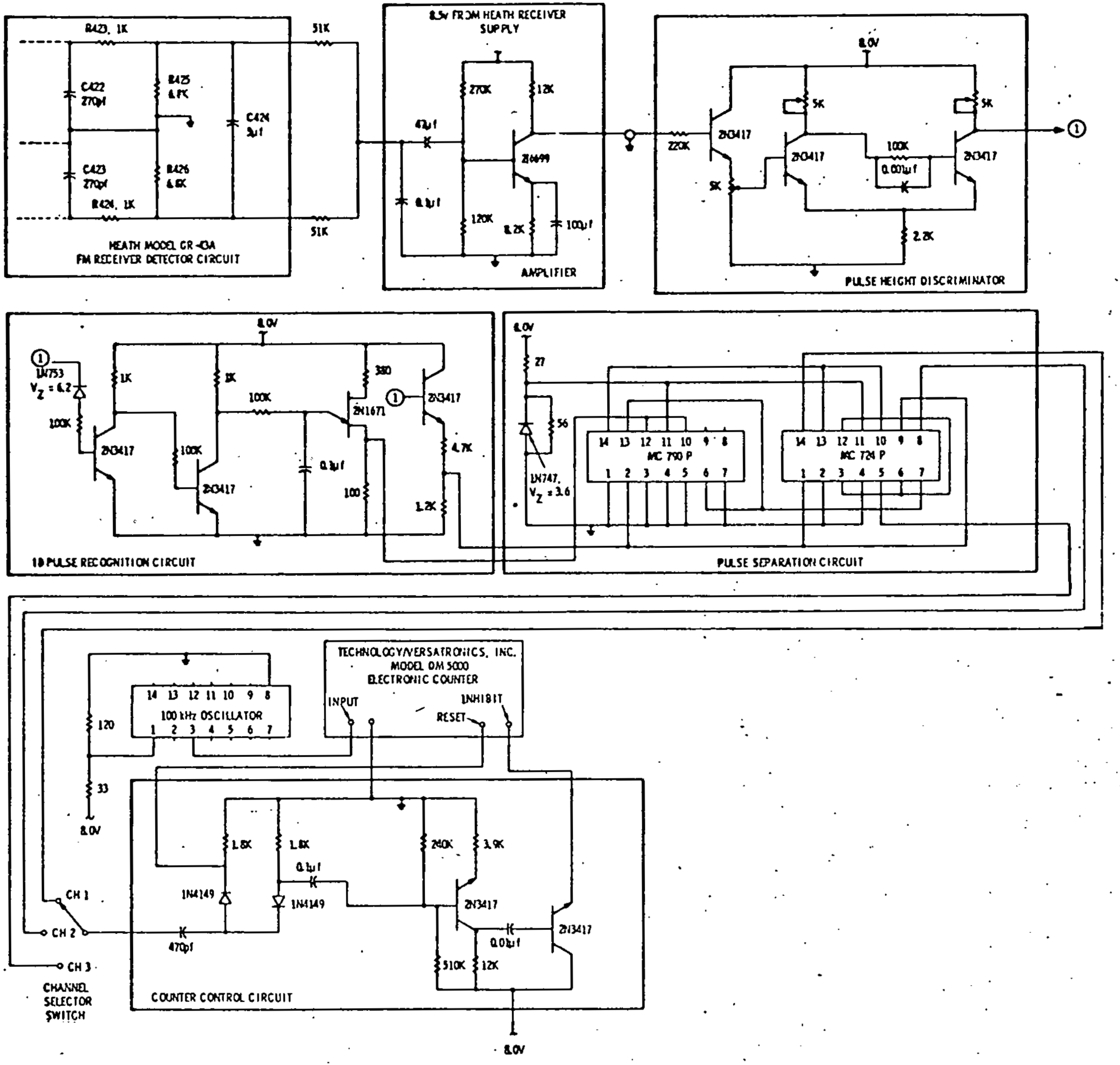


Figure 4. Circuit diagram of three-channel temperature telemetry receiver.

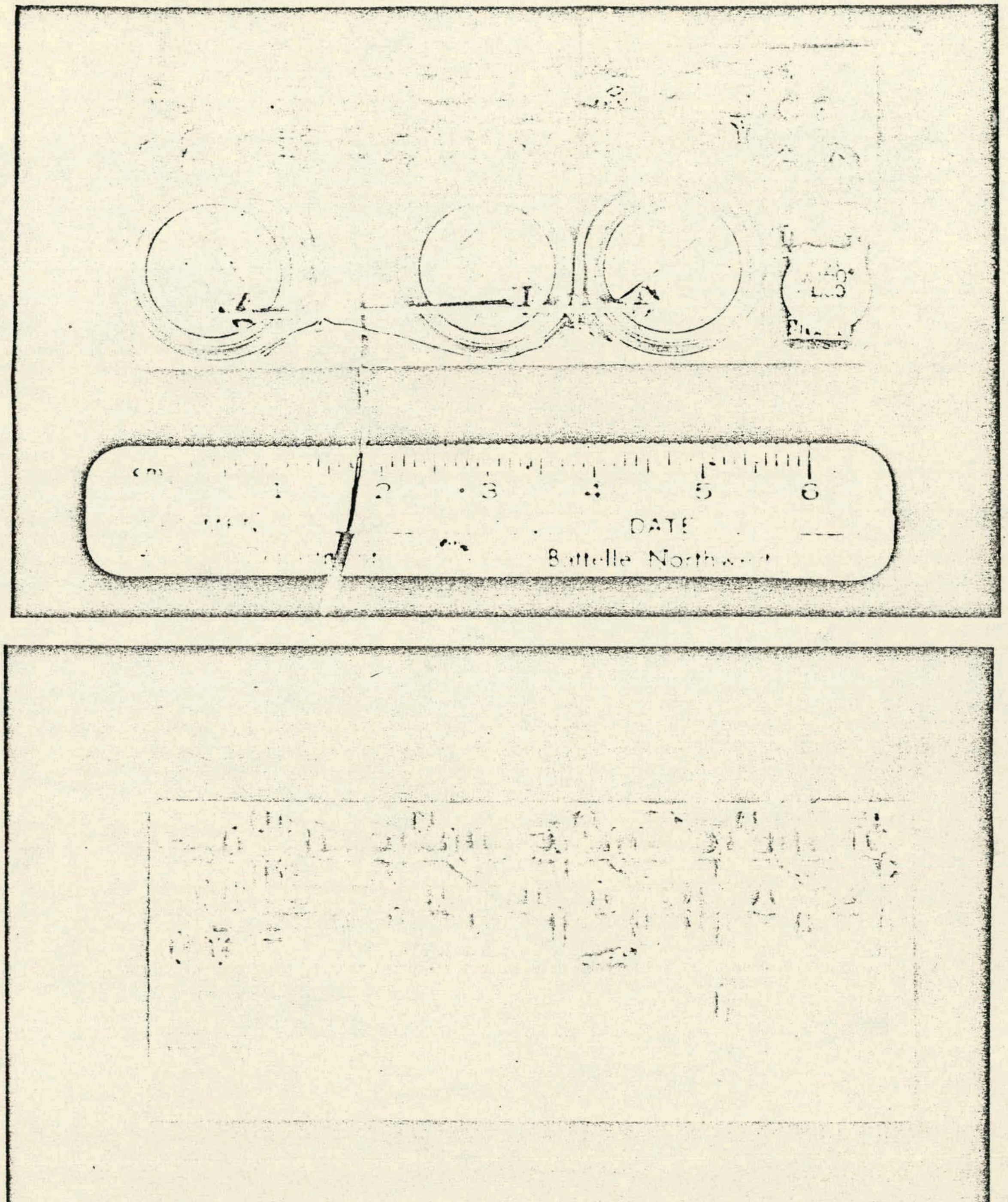


Figure 5. Photograph of complete telemetry transmitter prior to potting in radioisotope heat exchanger for animal implantation.

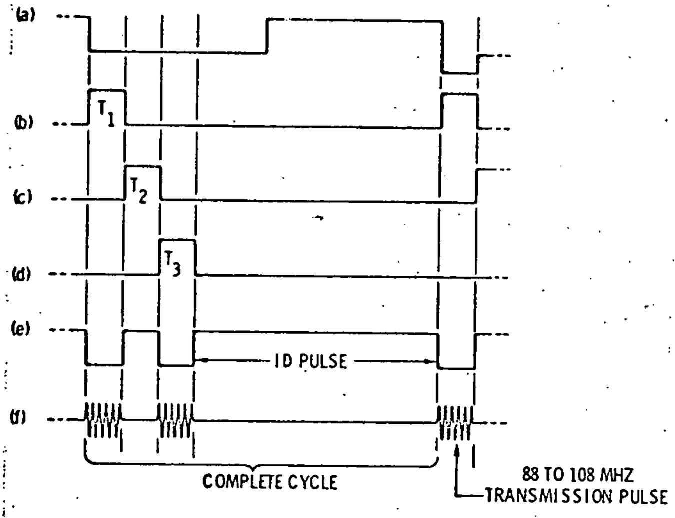


Figure 6. Telemetry transmitter waveforms:

(a) Output waveform at the collector of Q1 of the astable multivibrator.

(b,c,d) Output waveforms at the collector of Q1 of each of the temperature dependent mono monostable multivibrators. Length of pulses T_1, T_2, and T_3 are inversely proportional to the temperature sensed by thermistors 1, 2, and 3, respectively.

(e) The output waveform of the gating circuit. Pulse ID is used as an identification pulse in the telemetry receiver.

(f) Output waveform of the Belair Model M-5 integrated circuit FM Transmitter.

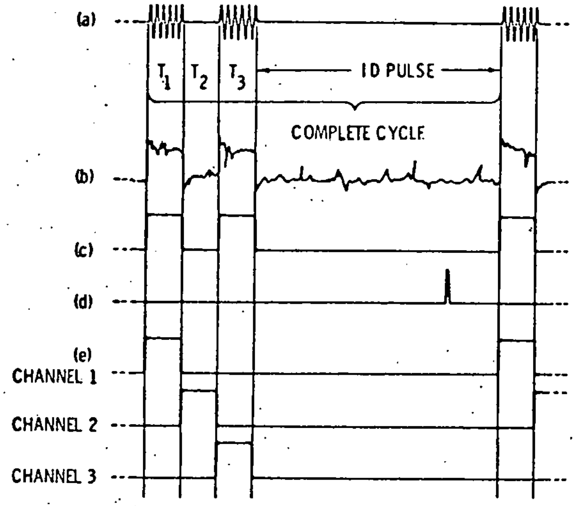


Figure 7. Typical waveform depicting the processing of the received signal in the Pulse Detection-Separation (PDS) network. (Refer to Figures 2 and 4.)

(a) Signal waveform received from Transmitter by Heath Model GR-43A portable FM receiver.

(b) Signal entering PDS network.

(c) Output waveform of Pulse Height Discriminator.

(d) Reset pulse from ID Pulse Recognition Circuit.

(e) Channel 1, 2, and 3 outputs of the Pulse Separation Circuit. These signals control the counting period of the electronic counter yielding a digital readout directly proportional to the respective pulse width, T_1, T_2, or T_3.