NON-INTRUSIVE DATA AQUISITION SYSTEM

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ABSTRACT

Previous solid rocket motor instrumentation was inadequate to correlate motor performance with analysis. This is particularly obvious when flight failures occur. The addition of instrumentation, both externally and internally, to the rocket motor has helped solve this problem. External instrumentation has been implemented quite easily with existing technology. However, internal instrumentation has been very difficult to implement. This has been mainly due to the complexity of breaching the motor case. A system was developed that transmits power through the case structure to a unique encoder/signal conditioner which then transmits the data back across the case structure for analysis. This was accomplished by magnetic coupling avoiding any disruption of the case structure. A detailed discussion of the magnetic coupling, signal conditioning and encoding functions will be presented.

INTRODUCTION

In the history of solid rocket motor flights, a number of unresolved failures have occurred. These failures went unresolved because they either could not be correlated with static motor firing performance data, or could not be diagnosed at all due to inadequate flight instrumentation data. A program was therefore developed to greatly increase the instrumentation on flight rocket motors.

Under this program, a portion of the instrumentation was designed to be placed inside the rocket motor between the case and the insulation. The purpose of this instrumentation was to measure such key motor design verification parameters as temperature, heat flow, and propellant stresses during motor burn. A major problem with this system was developing a safe, reliable means of routing power and signal through the motor case to these internal sensors. Drilling holes though the case would cause severe stresses and possible leak paths. Winding wires through the layers of Kevlar during motor fabrication would cause stresses an potential wire breakage. Even routing wires through the normal closures in the case had potential for wire breakage and high stresses at the closures. And since large quantities of sensors (up to 64) were considered, any hardwired scheme would have to allow for the routing of hundreds of wires to flight signal conditioning/data acquisition equipment via missile-level cabling.

One solution to this problem was to develop a system capable of routing power and signals through the motor case without the use of wires. This system would consist of (at least) two parts: An internal unit, which would be located inside the motor case in the same plane as the sensors; and an external unit, which would be located directly across the motor case from the internal unit. The internal unit would contain a power receiving section, an encoder section and a signal transmitting section. It would have to be small, extremely low-profiled, and contoured to fit the shape of the motor case. It would have to withstand pressures in excess of 1000 psi. All wiring to the sensors would have to be terminated at the unit without any gaps on stress risers.

An external unit would house a power coupling and data receiving section. The unit would also be rigid, light weight, and would contour to the motor case. The power coupler section would have to be very efficient and provide minimal interference to the signal circuitry.

This paper presents the design of a non-intrusive data acquisition system which was developed to meet these requirements.

This system was developed and delivered under contract to United Technologies Chemical Systems Division San Jose, Calif. The system was designed for use on the Trident II D5 third stage rocket motor development system.

SYSTEM DESCRIPTION

External System

As shown in figure 1, the external system receives the DC (28±6V) power from the rocket motor power source, converts it to a square wave for coupling across the case structure and generates the voltages required to operate the data coupler detector and the output buffer.

The received bi-phase level (BIØ-L) data stream from the internal unit is applied to differential line drivers capable of driving greater than 500 feet of twisted shielded pair cable.

Internal System

The internal system (see figure 2) derives its power from the external system via the power coupler. System voltages are created from the square wave coupled across the case structure. These system voltages are used for proper system operation and sensor excitation sources. The output of the sensors are conditioned as necessary, prior to routing to the Pulse Code Modulation (PCM) encoder. The PCM encoder accepts 64 differential channels of sensor data, amplifies where necessary, and converts the analog to its binary equivalent. The converted data are then merged with a frame sync code to form a serial non-return-to-zero (NRZ-L) data stream. This data stream is converted to BIØ-L and coupled across the case structure for further processing by the external unit.

The PCM encoder is a fixed format encoder utilizing CMOS circuits to reduce the power consumption. The format and the programmable gain amplifier are controlled by a CMOS PROM for versatility.

Programmable Gain Amplifier (PGA) Multiplexer

The Analog Multiplexer section accepts 64 differential inputs (see figure 3). The data signals are sequentially sent to the inputs of a differential programmable gain instrumentation amplifier (PGA) via Metal Oxide Semiconductor Field Effect Transistor (MOSFET) gates. The PGA amplifier output is applied to the input of a summing amplifier that functions as a thermocouple reference compensation circuit.

All input data are sampled by one of the eight monolithic 16 channel multiplexers that are combined to form the 64 differential inputs. These devices are constructed with a complementary MOS process with inputs protected from overvoltages exceeding either supply. Protection is provided against damage from overvoltages up to ±33V.

When addressed, the input data are routed to the PGA amplifier inputs. The monolithic amplifier used in this application is a controlled gain block, which features differential inputs (single ended output) and an accurate I/O gain relationship. As a complete amplification circuit, this device does not depend on external resistor matching for I/O isolation. It has a high Common Mode Rejection Ratio (100db) in any application. The amplifier gain is set by the ratio of resistors selected to provide the programmable gains. The four discrete gains are 500, 100, 50 and 1. The gain of one is used for the two internal channel monitors, scaled temperature and supply voltage.

The temperature of the internal unit is sensed by a thermocouple and scaled by an amplifier circuit (discussed with the signal conditioning) to provide the compensation signal (temperature information). This signal is summed with the thermocouple channels at the appropriate time by the analog switch. At all other times the summing amplifier receives a zero signal.

Analog-to-Digital (A/D) Format Control

The serial pulse amplitude modulated data stream (analog data) from the summing amplifier is encoded to its binary equivalent form by a sample and hold circuit and successive approximation A/D converter (see figure 4) prior to interleaving in the NRZ-L data stream. The sample and hold circuit samples the data for one word time period, then holds the data sample during its conversion to binary form during the next word period. The circuit accomplishes this function by charging a high quality polycarbonate capacitor to the sampled value, then switching the capacitor to a high input impedance buffer amplifier where the value is held until the conversion is complete.

The parallel data from the A/D converter are loaded into a parallel-to-serial shift register for conversion to serial form. The serial output is routed to a digital multiplexer for insertion into the serial NRZ-L data stream. This NRZ-L data stream is later converted to BIØ-L format for transmission.

The format control generates the timing signals required to select, convert, and format an input signal. The timing signals are based on CLK (a 50% duty cycle signal whose period is one bit time) and CT (a signal whose period is one word time, eight bits).

A CMOS programmable read only memory (PROM) is used to generate the gain control signal, the analog/sync select signal and the end of frame pulse. The PROM is a polysilicon fuseable link with byte-wide organization. The PROM address inputs come from a binary counter, operated at the system word rate.

Frame sync code is generated by two CMOS edge triggered parallel to serial shift registers. The sync code (1110101110010000) is loaded into the registers at the beginning of every frame to provide frame synchronization.

The basic system timing is established by a crystal oscillator circuit utilizing a CMOS hex inverter, a crystal, and an appropriate drive circuit, to form a simple yet highly reliable reference oscillator. This circuit provides a bit rate stability of 0.1%.

Signal Conditioning

The signal conditioning supplied for this application consisted of a multiplexed constant current supply for stress tranducers and shear gage excitations and thermocouple reference junction compensation and termination.

Current Source Excitation

Figure 5 is a schematic of the basic constant current circuit that was used to supply the constant current requirements. The formula for determining the load current IL, is:

$$IL = \frac{R3*Vref}{R1*R5}$$

Output current adjustment (if required) is accomplished by changing the value of one of the R1 resistors. The circuit as shown will yield a current variation of less than 0.5% over the operating temperature range. Of course, any change in the value of Vref will have a direct effect on the output current. To reduce the effect this variation has on system operation, the Vref input is the reference for the A/D converter and as such any drift in the constant current caused by the reference will tend to be cancelled.

Also contained in figure 5 is the functional schematic of the pulse current excitation circuit (PCE). Unlike classical methods of continuous bridge excitation, the PCE supplies excitation current only to the bridge being sampled by the PCM encoder. The PCM format control determines which analog multiplexer channel will be selected. Current is routed through the selected analog multiplexer to the sensor for one word period. This time period allows for the excitation current to settle before the PCM encoder samples the model of the sensor circuitry. As indicated the current pulse is completely stable in 45 nsec. This is significantly less than the word time of 16 usec.

Thermocouple Termination

Since every pair of dissimilar metals in contact constitutes a thermocouple (including copper/solder) and since a useful electrical circuit will contain at least two contacts in series, measurements with thermocouples must be implemented in a manner which minimizes undesired contributions of incidental thermocouples and provide a suitable reference.

Thermocouple compensation techniques include physical references (ice-point cells), ambient temperature reference junctions and the electronic cold-junction compensators. The most suitable form for this application is cold junction compensation, primarily due to the physical problems. The thermocouples (see figure 7) are terminated at an iso-thermal block and the temperature of the block is measured by a suitable device. The temperature measuring device chosen for this application is the Analog Devices AD590 temperature sensor. This device outputs a current that is directly proportional to the temperature. The ouptut current is then scaled and used to compensate for the iso-thermal block temperature.

Due to extremely small volume constraints and the location where it would be used, standard isothermal blocks for thermocouple termination were not deemed practical. The chromelalumel thermocouples were soldered (using high temperature silver solder) directly to the internal unit printed circuit board. After testing the unit was potted solid with an epoxy base material. When cured this material provided the unit with a homogenous structure that forms the required isothermal block. The AD590 temperature sensor was mounted to the printed circuit board in the same location as the terminated thermocouples. Thus, the sensor maintains the same temperature as the thermocouples.

Power and Signal Coupling

The couplers must transfer energy to the internal electronics and transducers while also receiving the acquired data from the internal electronics.

Field Choice

The primary decision to be made was which force field, electric or magnetic, should be employed. In considering the electric field case, a coupler could be designed using a set of parallel plate capacitors and a oscillating current generator. The current generator would be connected to two electrodes and the electric field would induce current to the internal side for power. A similiar approach would be used for the signal coupler. The initial analysis indicated the external volts required would be extremely high due to the inherent low capacitance of such a system.

As previously indicated, the magnetic field was selected for the power and signal couplers.

Core Geometry

The magnetic field caused by a flowing current is controlled by the geometry of the current carrying conductor. When the current carrying conductor is formed into the proper shape, a magnetic field penetrates into the internal side of the coupler and is transformed back to a flowing current. Choice of coupler geometry is made by trading-off efficiency with the physical space available. The height contraint of 0.25"-0.30 ruled out the use of several geometries. Toroidal, pot core and C-cores were determined to be unuseable with this height restraint.

The geometry for the power and signal coupler was chosen to be the disc core. This geometry is shown in figure 8a and 8b. A disc core with windings external to the core represents a short cylindrical solenoid. Figure 8c is a photograph of the actual magnetic field shown by the orientation of iron filings. Along the vertical center of figure 8a, the flux will be perpendicular to the flat face of the core, toward either edge of the core the flux will diverge outward. Not all the flux generated by the primary will reach the secondary; however windings can be added without increasing the height of the core to achieve the required voltage at the secondary.

The general shape of the magnetic field of figure 8a will result regardless of the permeability of the core material. However, the presence of magnetic material increases flux density due to the reduced magnetic path length.

Power Coupler

The applied unregulated voltage in the range of 28V passes through a reverse polarity protection diode (see figure 9) and EMI filter to a power switch controlled by a pulse width modulator circuit. The EMI filter is a Pi type consisting of an input capacitor, series inductor and output capacitor.

The pulse width modulator (PWM2) operates at a fixed pulse width and less than 50% duty cycle to ensure that there will be no destructive simultaneous conduction in the driver transistors. Storage times in the driver transistors ranged from 1 to 2 usec. If driver 2 gets turned on before driver 1 has completely turned off, there would be a destructive current spike in driver 2 due to the primary voltage coupling of the transformer. Since the magnetic coupling from primary to secondary is less than perfect, because of the relatively large air gap, the collapsing magnetic field each half cycle will cause a voltage spike as the field cuts through primary windings. This voltage spike must be clamped to a safe level to prevent secondary breakdown. Ultra-fast recovery diodes are used as voltage clamps while driver transistors rated at 150 volts permit safe operation.

Signal Coupler

The geometry used for the signal coupler is similar but smaller than the geometry for the power coupler since the power handling requirements are significantly less. Figure 10 is a block diagram of the signal coupler.

The input to the signal coupler is encoded as BIØ-L. This code ensures that there will be no DC content in the transmitted signal. The reason DC content can not be permitted is that over time the primary of the signal transformer will saturate. It would be the same as applying a non-zero DC voltage to the primary. Eventually the core would “walk up” the hysteresis loop and one of the drivers would try to switch a low impedance to the supply drawing excessive current. Although the transistors used for the signal coupler are much faster than those used in the power coupler (which thay have to be since the frequency is much higher) they still have some storage time. The use of a blanking pulse generator makes sure that for this period of time, drive is removed from both transistors. On the external side are two damping resistors critically damping the parallel resonant circuit formed by the secondary inductance and its own ditributed capacitance. The high input impedance of the comparator will not sufficiently damp this circuit alone. Finally, a high speed comparator transforms the received singal back to TTL levels.

Physical Considerations

Figure 8c shows a photograph of an actual magnetic field from a magnetic coupler primary carrying a current of 4 amperes. It is clear that at the edges of the core the field becomes quite circular, and the changing field could induce an EMF in an adjacent coil of wire (or etch). This is exactly what occurred in the first unit. Due to the very small size requirements a large separation between the coupler and input circuitry was not possible. Since the primary power coupler generates stronger fields than the secondary due to higher current, shielding is more critical on the internal side. However, in order to prevent penetration of the power coupler field into the signal coupler windings causing data errors, high permeability Mu metal shields were placed over both cores. This technique forces the field remaining from the power coupler to follow the contour of the Mu metal shield instead of traversing laterally into the signal coupler. A Mu metal shield was also used in the internal unit to help prevent the power coupler signal from entering the high gain amplifier inputs. The output data showed a predominant frequency content at the power coupler switching frequency. Since this frequency is substantially higher than any expected data, standard data reduction techniques (averaging was used) easily removed this error. Future designs will incorporate larger area cores in the internal unit (this reduces fringing) and greater separation between inputs and couplers.

Mechanical Description

The surface mount (primarily flat packs) packaging concept for the system was selected to provide optimum structural integrity in the dynamic environments while allowing heat dissipation and compliance with the specification requirement for minimum size.

External Unit

The external equipment (see figure 11) consists of a single printed circuit board potted solidly into a 6061-T6 aluminum chassis. The potting compound is a one part general purpose epoxy manufactured by Emerson & Cuming, Inc. This potting compound provides a homogenous thermal path for power dissipation in the switching transistors. Also, a potted unit is easier to shape to the desired curvature of the case structure.

As indicated, the external unit was required to fit the curvature of a 16 inch diameter rocket motor case while maintaining as low a profile as possible. The height for this diameter case was 0.762 inches. A single 15-pin connector was provided for the application of power and extraction of data. The flanges on each end of the unit were used to secure the unit to the outside of the rocket motor case.

Internal Unit

One of the most challenging aspects of the project was the packaging of the internal unit. This unit had to conform to the curvature of the case, and in addition to the interesting shape, a number of other requirements had to be met. These requirements included thermal, pressure, water immersion, acceleration, vibration and shock.

Figure 12 is an outline drawing of the internal unit. The flat cables exiting both sides of the unit are the sensor inputs/sensor excitation. All surfaces of the internal unit are designed to present as smooth a transition as possible to prevent voids form being formed when the unit is installed in the rocket motor. When installed in the rocket motor the unit is completely surrounded with an insulating material that serves to protect the unit from the burning fuel. This insulation also causes the internal temperature of the unit to rise since a good thermal path is not available for heat transfer. This condition dictated the design of a very low power unit (the internal requirement was approximately 2 watts).

Considering the thermal shock of 300 deg F for 4 days, a pressure requirement of 1077 psi. (testing indicated many IC packages can't withstand this pressure), complete immersion in sea water and the other operating conditions it was determined that a solid potted unit would be required to meet the specifications.

Due to the extreme curvature of the motor case a flexible printed circuit board was required. The board was formed prior to component installation and held in the correct shape by a potting fixture. Figure 13 shows a cross section of the unit in the potting mold. The shape of the flexible circuit board can be seen with the power coupler installed. The eight screws shown are used to position the coupler and printed wiring board prior to potting. The position of the coupler within the unit is critical since any variation in the core depth (inside the internal unit) will cause a corresponding loss in coupling efficiency.

After significant preliminary testing the unit was placed in the mold for potting. The initial unit that was potted did not function properly. This was later determined to be due to incorrect procedures during the potting process causing the printed wiring board to be damaged. This was corrected in the mold and testing during the potting process was implemented. These changes resulted in units being successfully potted.

Testing of the units was accomplished with internal/external pairs separated with an insulator to simulate the case. Both internal and external units present special testing problems once potted solid, since each unit requires the coupling of power and/or signal to operate properly.

CONCLUSION

A system has been designed, developed and produced that will allow the acquisition of data in the hostile environment of a rocket motor The system utilizes magnetic coupling to avoid violating the physical integrity of the case structure. Low power, small size and non-intrusive acquisition methods make this a truly unique telemetry system.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. Glen Campagna of United Technologies Corporation for his invaluable contributions to this paper and his considerable time and effort contributed during the project.

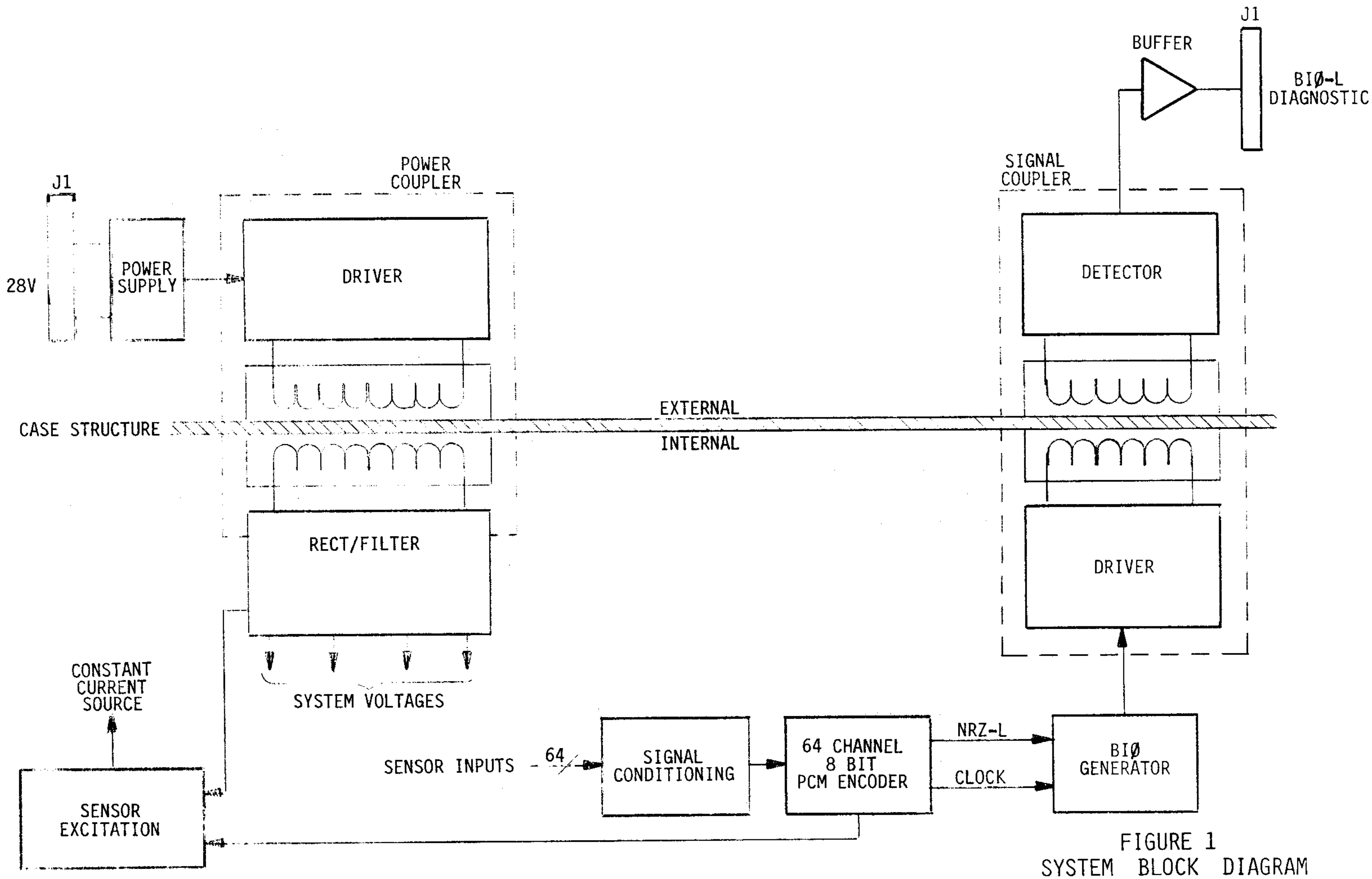


FIGURE 1
SYSTEM BLOCK DIAGRAM

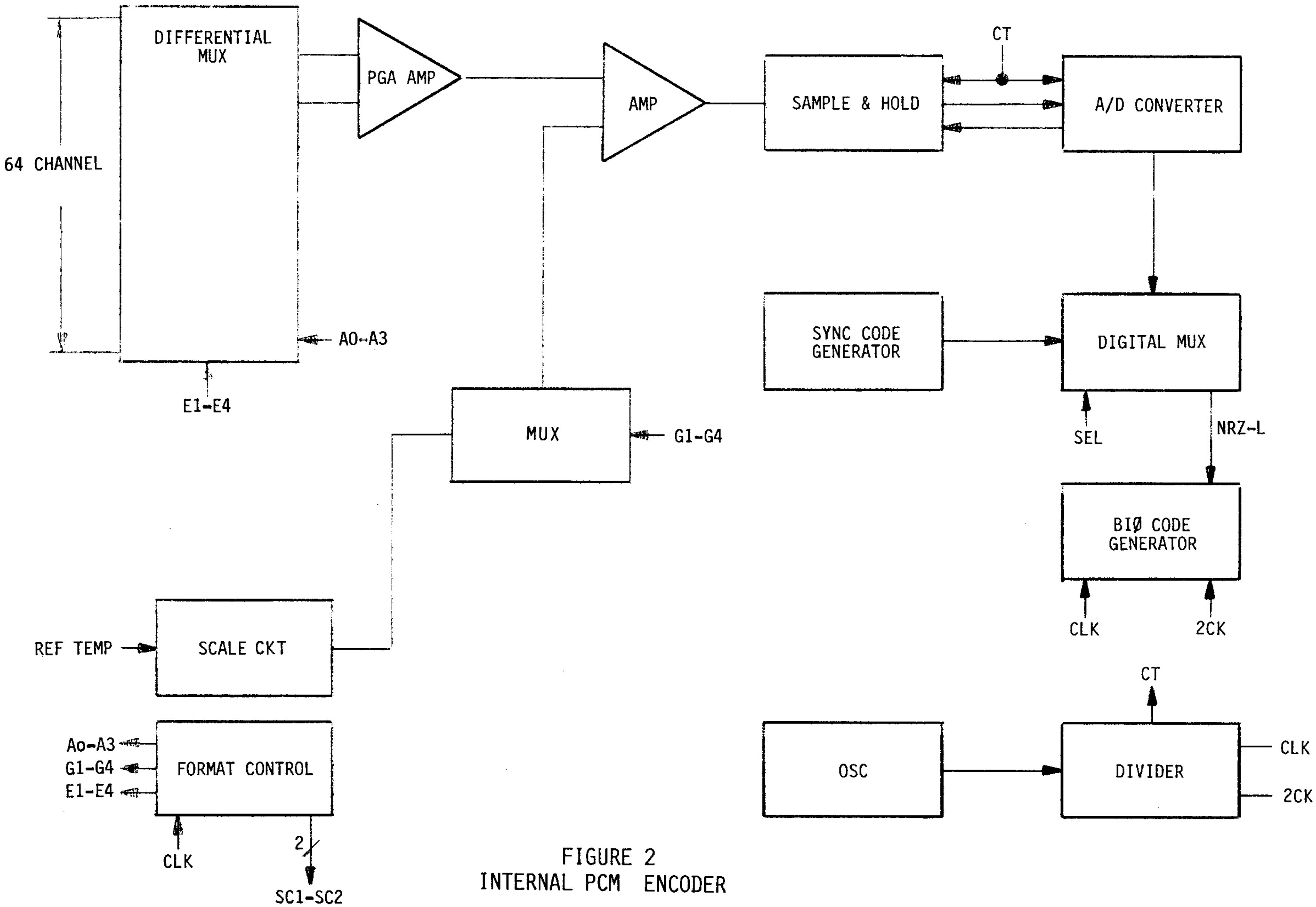


FIGURE 2
INTERNAL PCM ENCODER

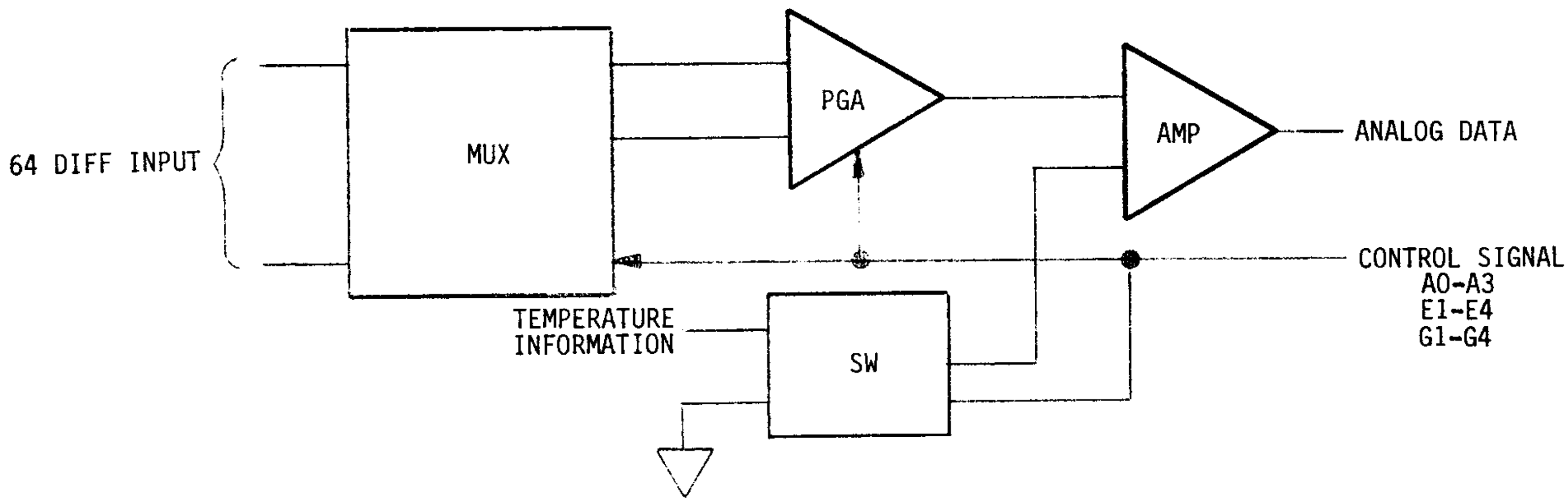


FIGURE 3
PGA MULTIPLEXER

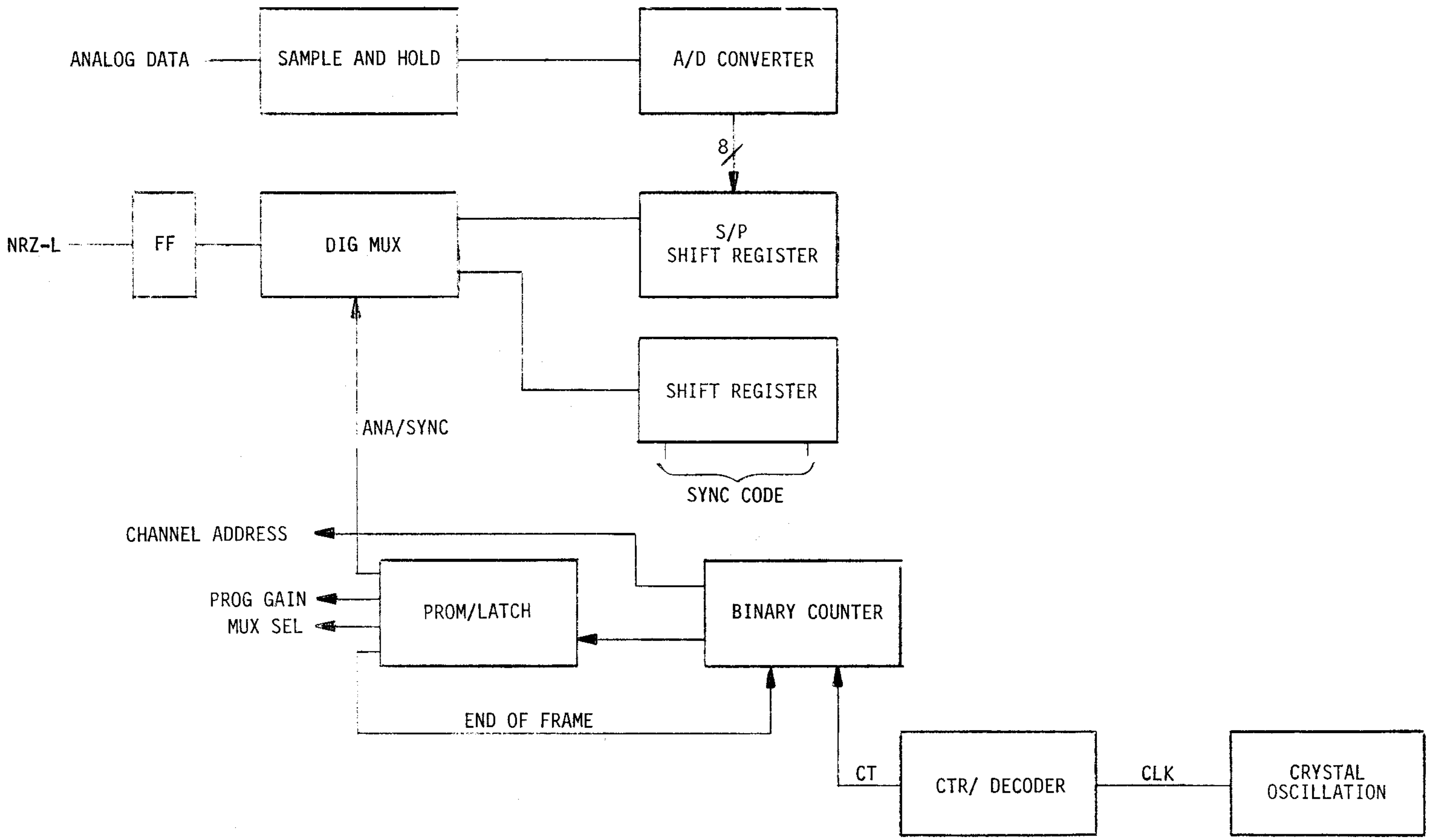
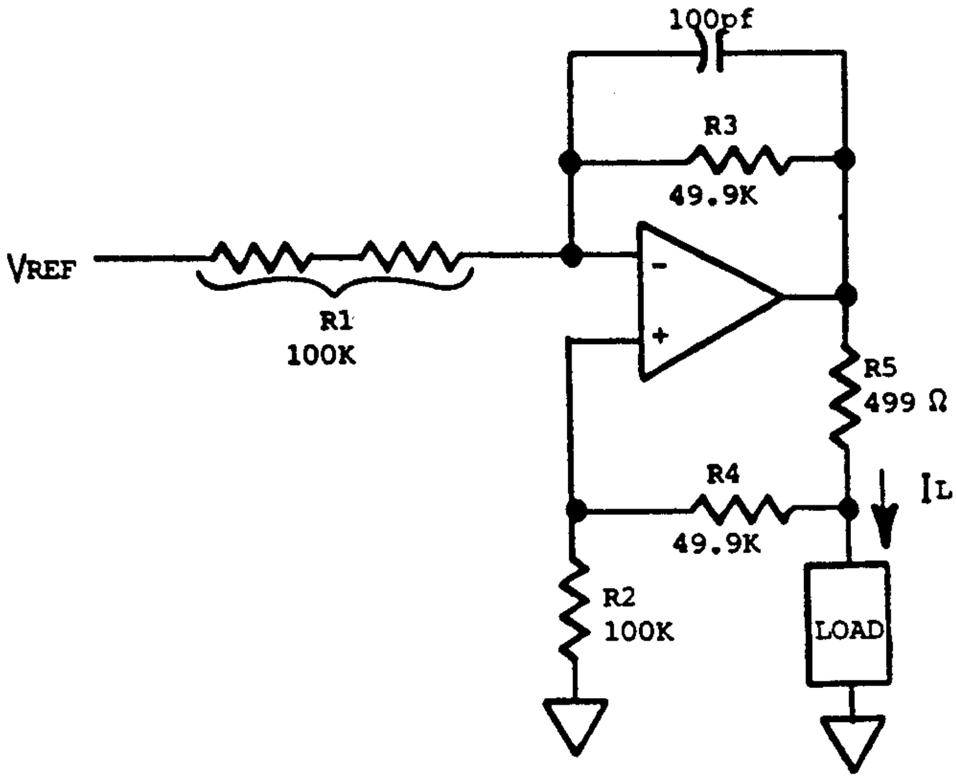


FIGURE 4
A/D FORMAT CONTROL



BASIC CURRENT SOURCE

$$I_L = \frac{R3\ VREF}{R1\ \ R5} = \frac{(49.9K)\ VREF}{(100K)\ \ (49.9)} = (1 \times 10^{-3})\ VREF$$

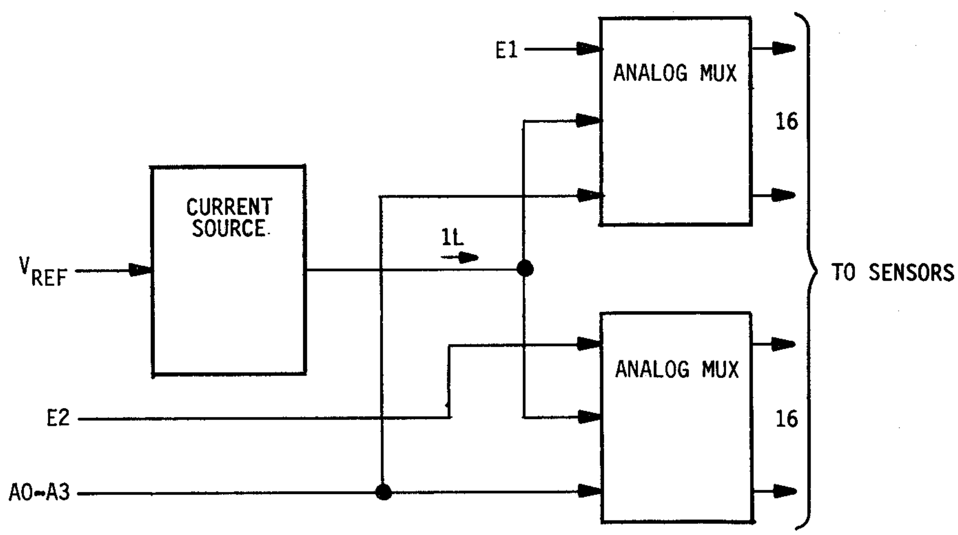
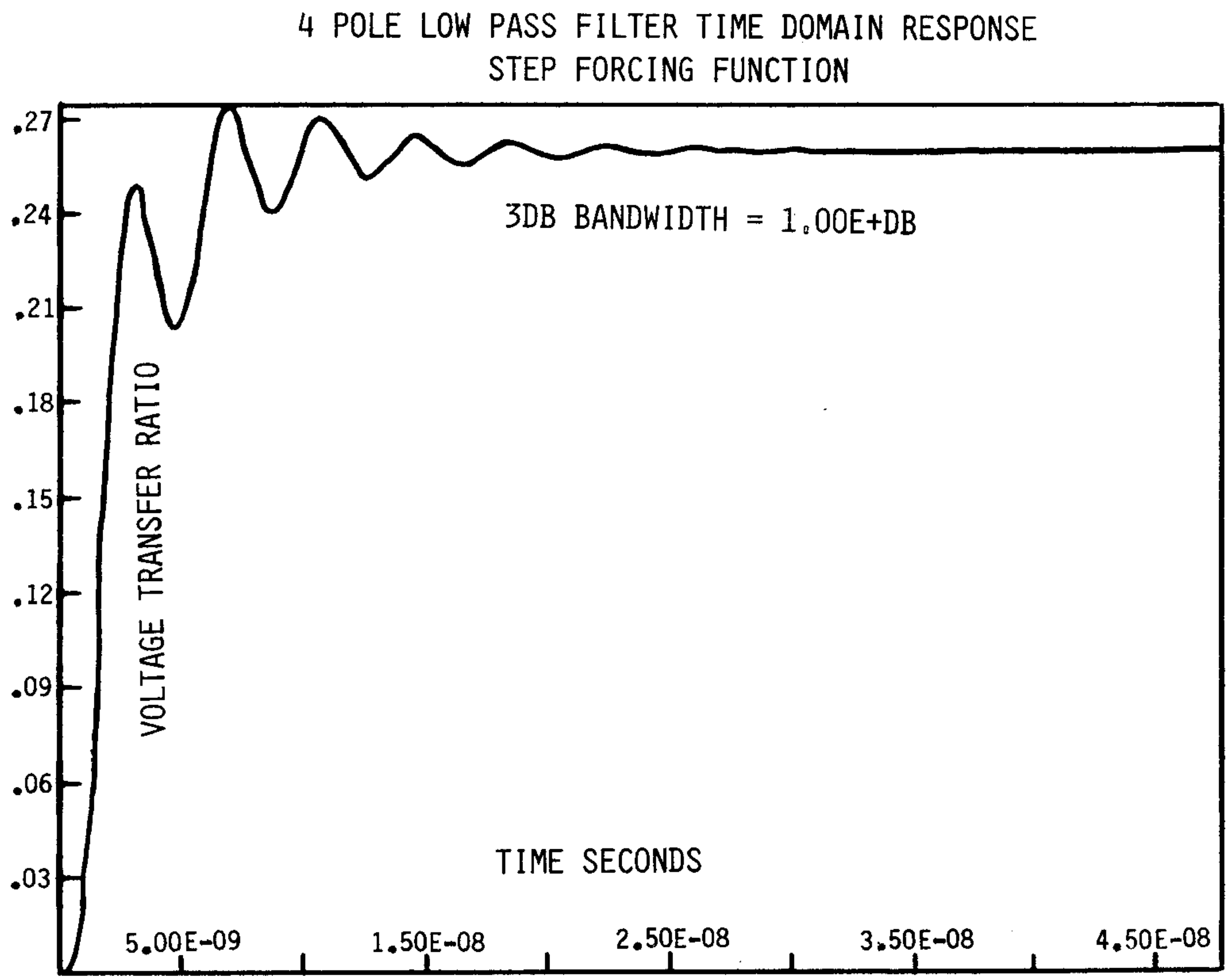


FIGURE 5
CURRENT EXCITATION SOURCE



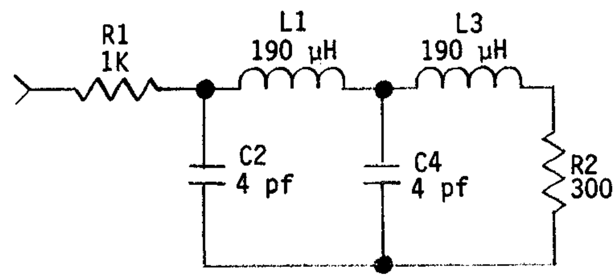


FIGURE 6
STEP RESPONSE
OF CURRENT SOURCE

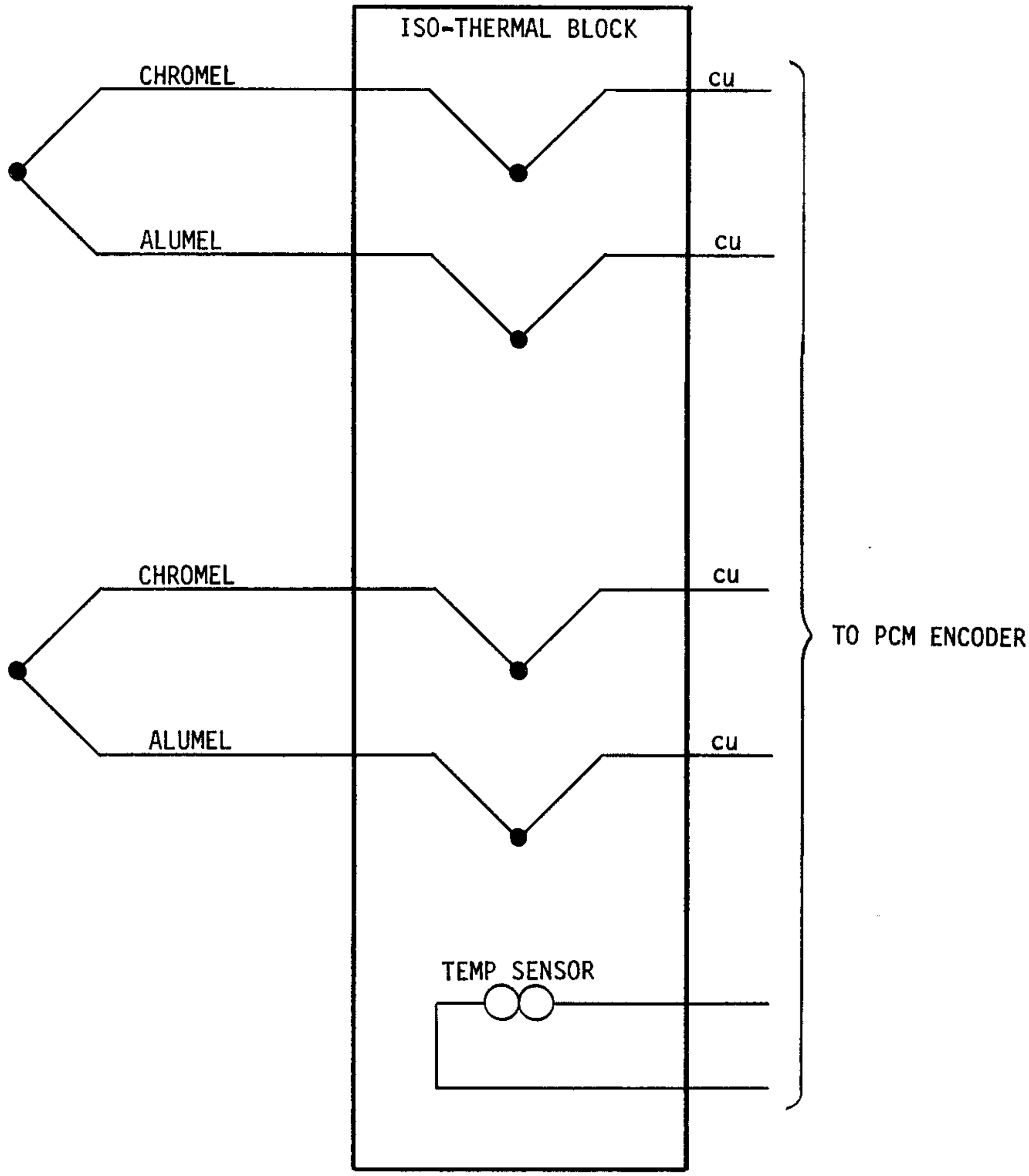


FIGURE 7
THERMOCOUPLE TERMINATION

FIGURE 8A

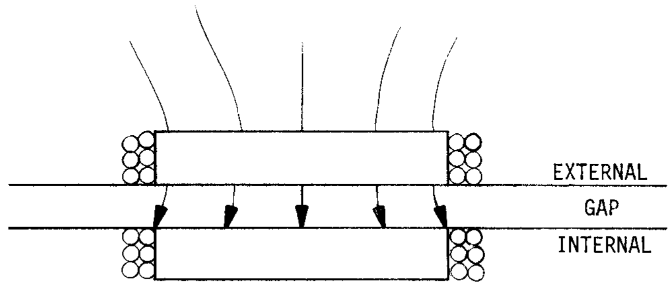


FIGURE 8B

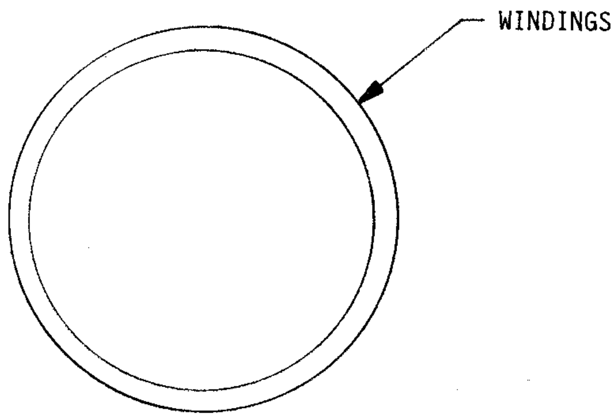


FIGURE 8C

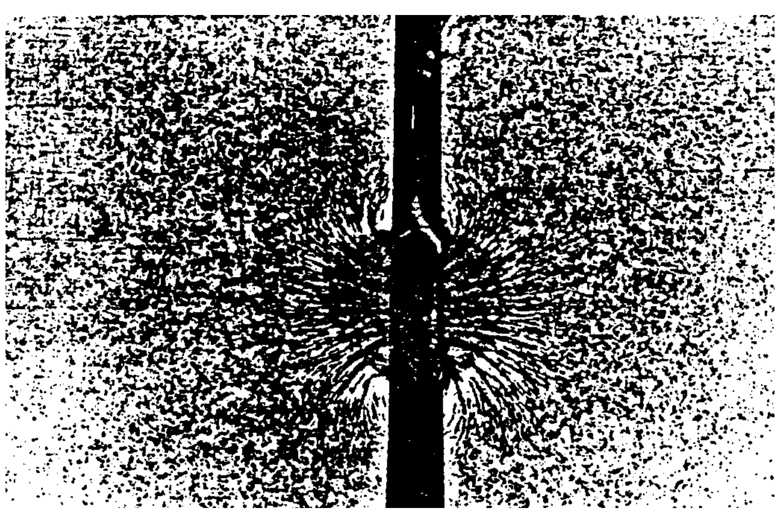


FIGURE 8
CORE GEOMETRY

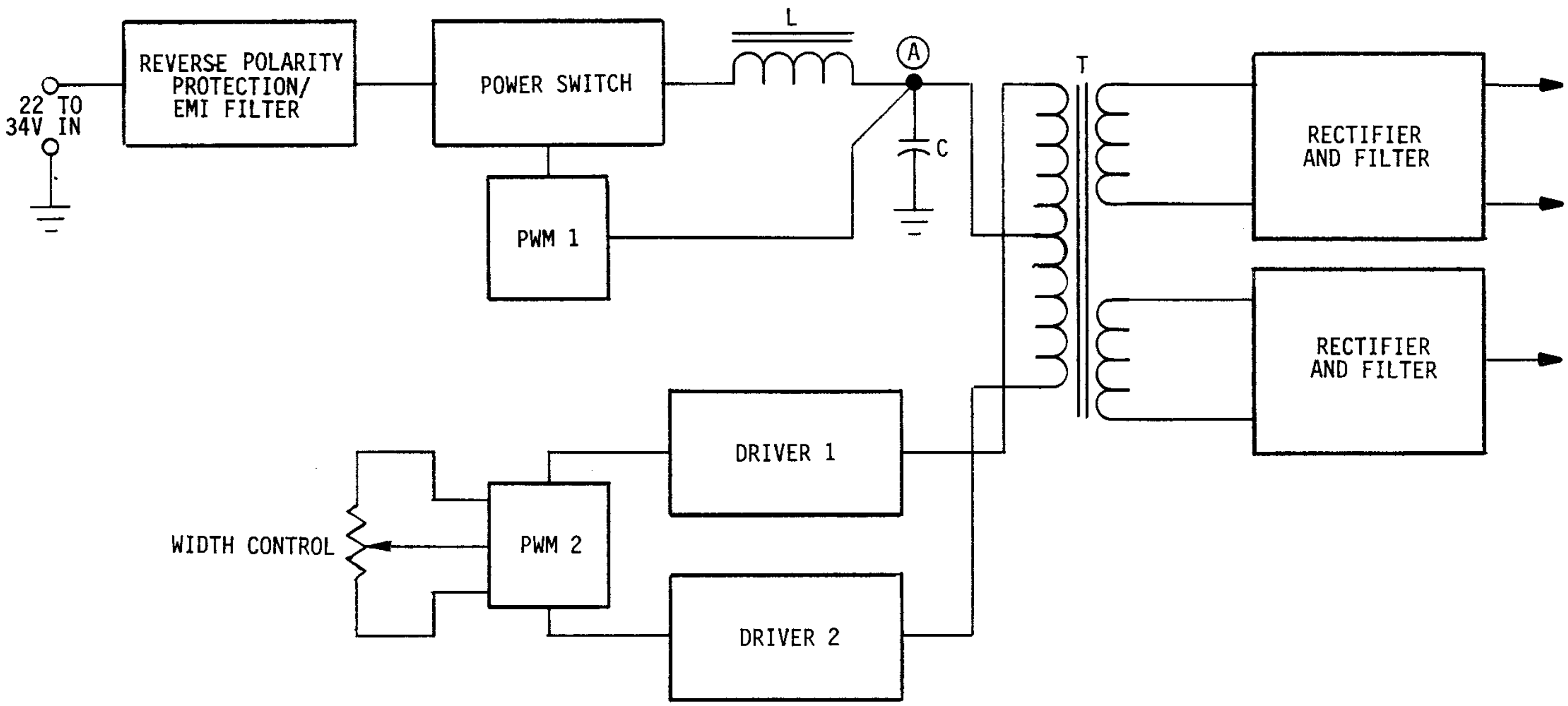


FIGURE 9
POWER COUPLER

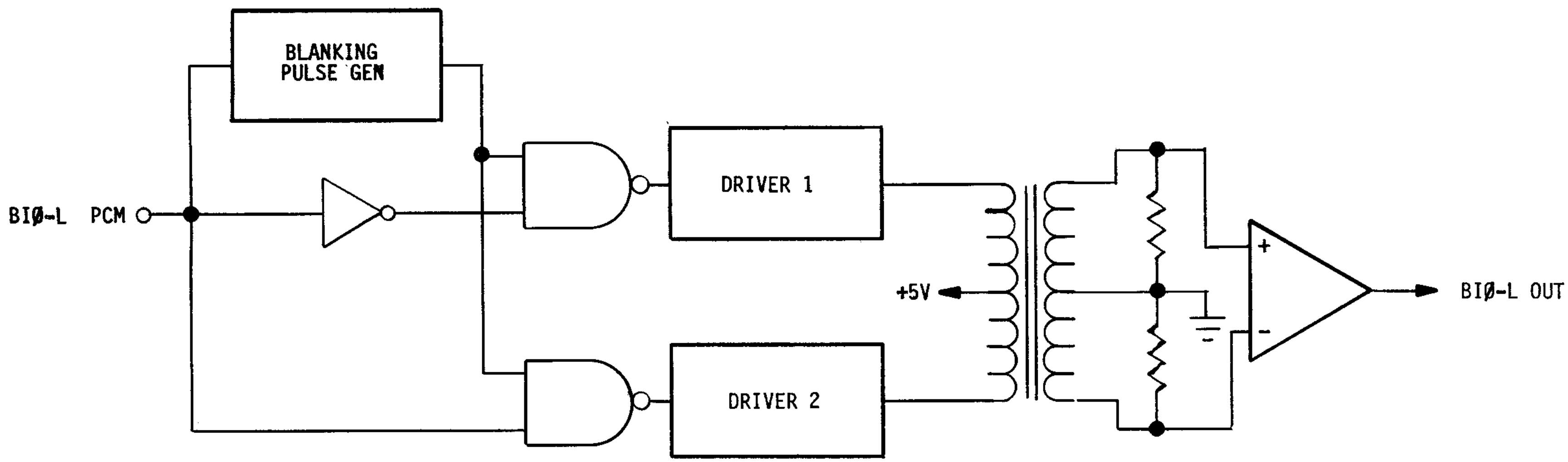


FIGURE 10
SIGNAL COUPLER

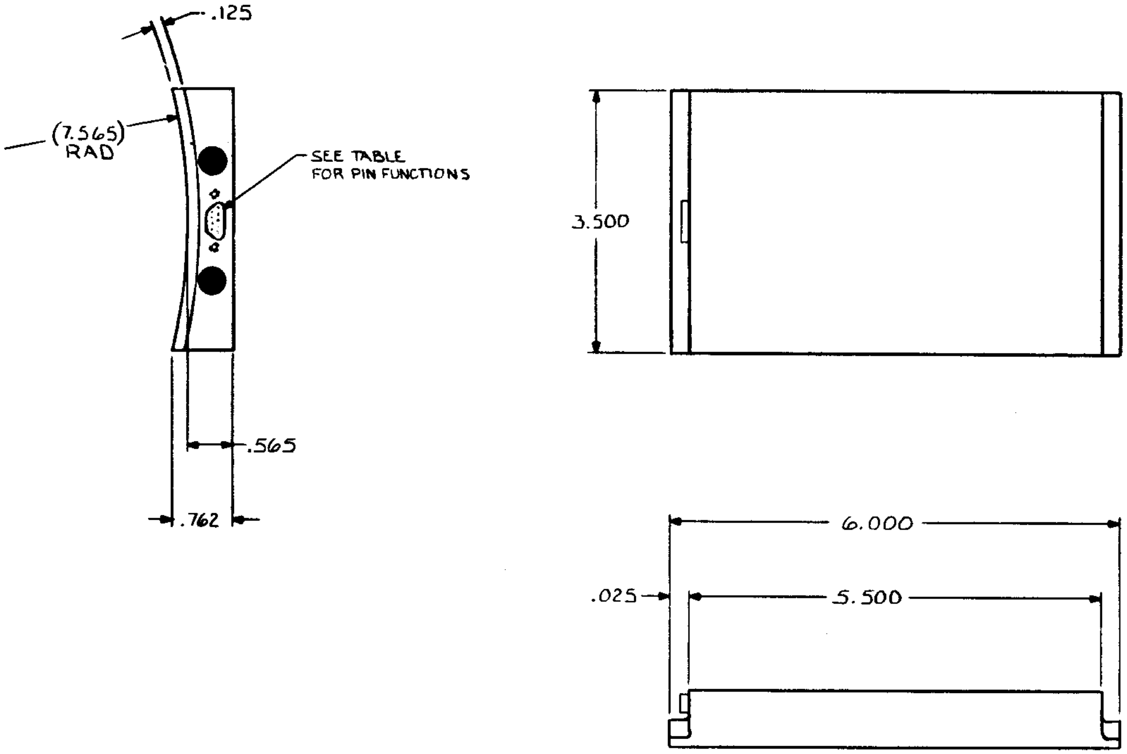


TABLE	
PIN	FUNCTION
1	+28V
2	(1) BIØ-L +
3	(1) BIØ-L −
4	28V RETURN
5	+28V
6	(1) BIØ-L +
7	TEST POINT
8	(1) BIØ-L −
9	28V RETURN
10	(2) BIØ-L +
11	(2) BIØ-L −
12	NC
13	NC
14	NC
15	CHASSIS GND

FIGURE 11
OUTLINE DRAWING
EXTERNAL UNIT

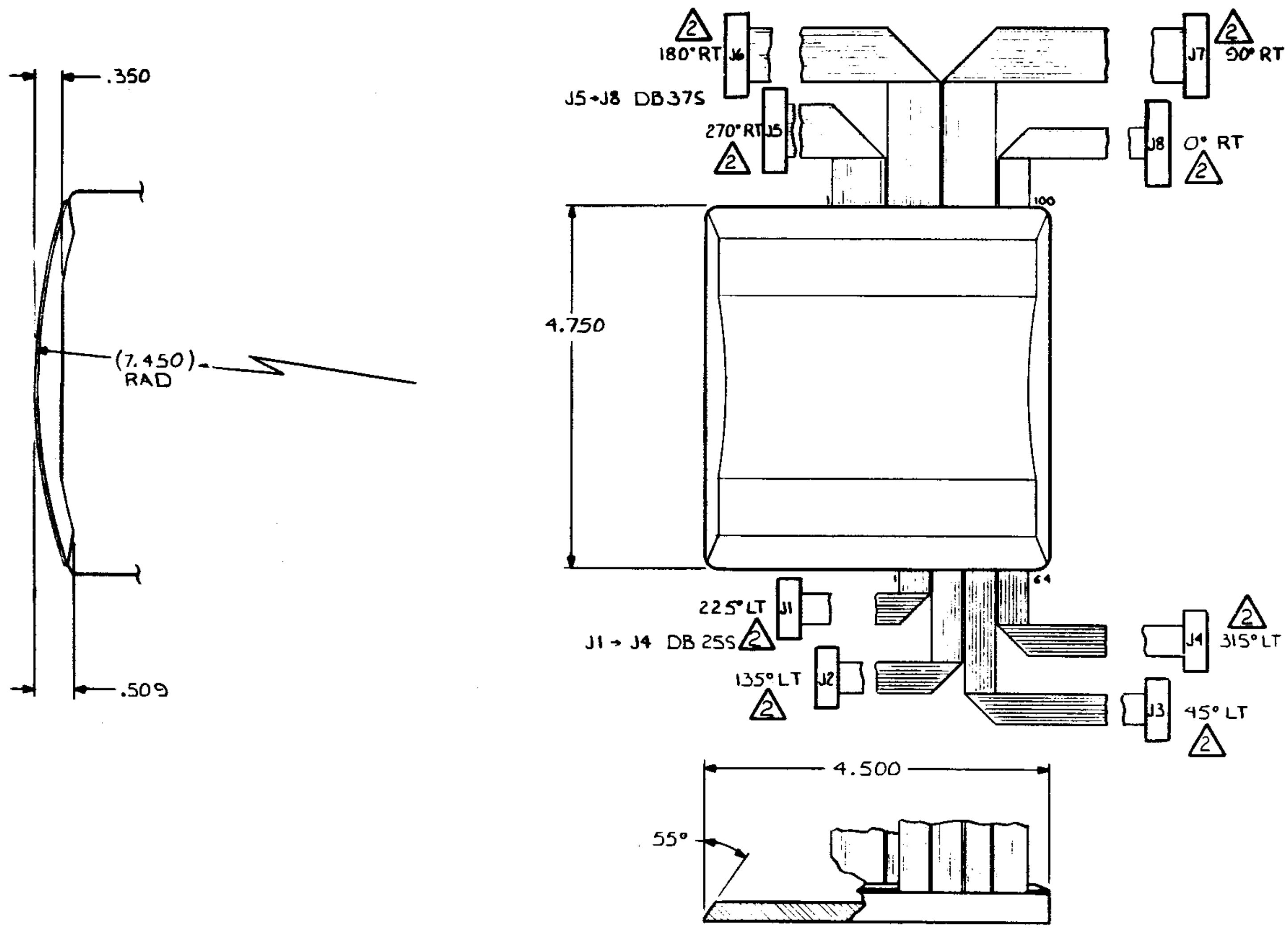


FIGURE 12
OUTLINE DRAWING
INTERNAL UNIT

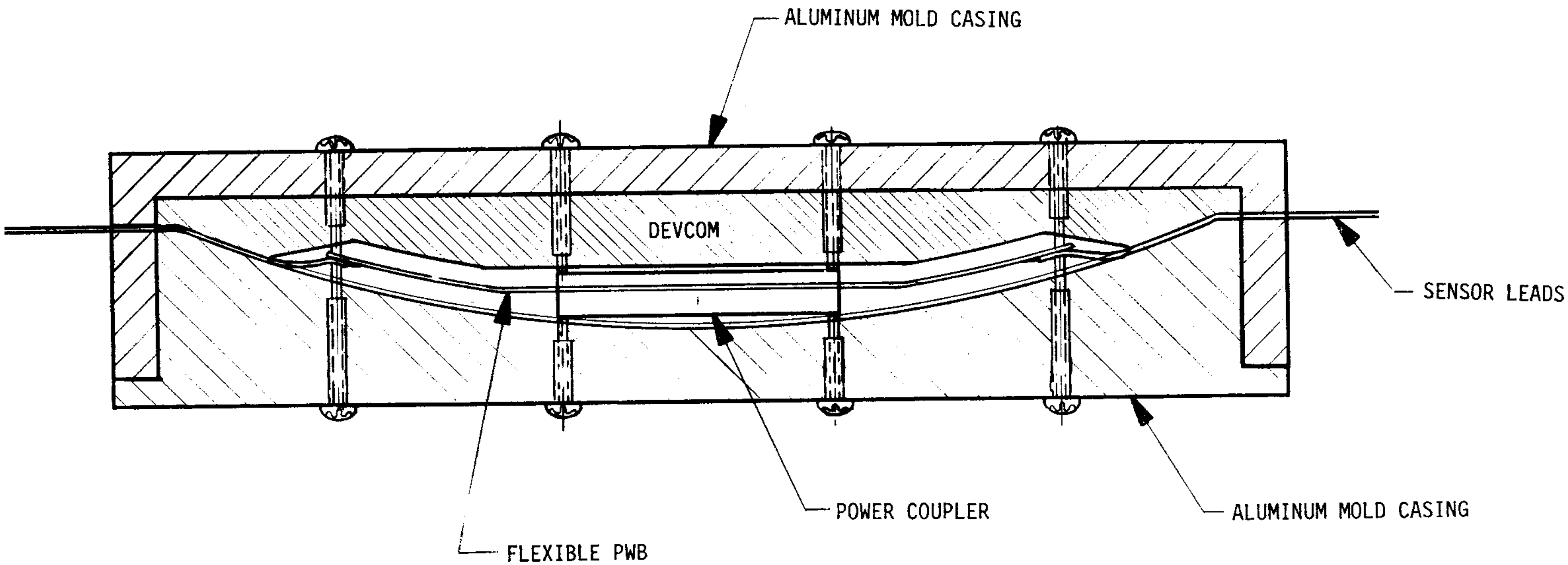


FIGURE 13
POTTING MOLD CROSS SECTION