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DEVELOPMENT OF A P/M LINE SENSOR

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13. ABSTRACT

This report describes advanced development of a plated wire line sensor. The sensor consists of a transducer (50-meter length), a battery pack, sensor electronics, and an interconnect cable to link the battery pack with the sensor electronics. One transducer has been evaluated in a field situation with good results for the stage of development. Five models were constructed and delivered for Air Force evaluation.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Sensor						
Transducer						
Battery Pack						
Interconnect Cable						
Driver/Detector						

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FOREWORD

This final report was prepared by Honeywell, Incorporated, Government and Aeronautical Products Division, 600 Second Street North, Hopkins, Minnesota, for Rome Air Development Center, Griffiss Air Force Base, New York, under Contract F30602-72-C-0040, Job Order Number 681E0318. RADC program monitors were Mr. James Briggs and Mr. Eric Winkler, both of DCTS.

This contract was for advanced development of a pressure sensitive plated wire line sensor. The effort was begun 3 December 1971 and completed 18 December 1972.

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS).

This technical report has been reviewed and is approved.

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SECTION I
INTRODUCTION

Line sensing in military applications may be defined as the technique of detecting the passage of man or vehicle across a given boundary or line. This can be implemented by use of a large number of point sensors spaced evenly along a boundary or by a single distributed line sensor. The Pressure/Magnetic (P/M) Line Sensor is a distributed single line approach.

In the P/M Line Sensor, a plated wire is used as the center conductor in a conventional coaxial cable. This cable forms a distributed transducer when buried in the ground. The transduction mechanism utilized in this approach is one of converting a ground pressure wave into localized strain on the transducer, producing an electrical output.

This report covers work performed toward development of the P/M transducer and associated electronics.

SECTION II
SUMMARY

This contract involved three major areas: transducer development, electronics development, and logic development. Program effort resulted in development of a continuous line sensor, 50 meters long, capable of detecting personnel intruders crossing the line.

Primary effort on this program was to develop a workable 100-meter, pressure-sensitive plated wire line sensor prototype. This was not accomplished, but significant progress toward the goal was achieved.

A 50-meter transducer has been developed and deployed to demonstrate the feasibility of this type of device. However, this transducer shows some areas of reduced sensitivity. This problem will require additional effort in both transducer and plated wire materials/characteristics areas.

The developed transducer is pressure-sensitive, utilizing both the plated wire properties of the line and its coaxial cable characteristics. This results in a detection band of 3 feet on either side of the wire for an average person crossing the line.

Electronics for this device has been developed and displays good performance in a field environment. The logic provides good detection but needs improvement in false target rejection. The extent of logic performance, however, will only be known after additional field evaluation.

This program has verified feasibility of the P/M Line Sensor and identified design parameters requiring additional development for consistent, improved performance in the field.

SECTION III
PROGRAM OBJECTIVES AND DESIGN GOALS

The objective of this program was development of a Pressure/Magnetic (P/M) Line Sensor consisting of a 100-meter transducer and associated electronics; this plated wire line sensor was to be capable of field testing and data collection. At completion of the program, ten sets of 100-meter transducers and five models of the driver/detector/decision logic electronics were to be delivered.

This program concerns the study, development, and fabrication of the sensor. Investigations included a transducer material and configuration study to optimize shape and size factors and sensitivity. In addition, driver/detector and logic techniques and means of decreasing battery drain for long life were investigated.

The following items were established as design goals:

1. Transducer cable size comparable to the RG-170/190 series cable.

2. Transducer sensitivity of six microvolts peak/0.005-inch deflection/12-inch span.

3. System detection of intruders of weight greater than 100 pounds.

4. System rejection of intruders of weight less than 20 pounds.

5. Transducer leakage radiation less than that of RG-174 cable driven at transducer drive frequency and amplitude.

6. System reliability of 90 percent for a six-month period.

SECTION IV
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. A 50- or 100-meter line sensor utilizing a plated wire transducer appears to be a feasible concept.

2. Performance and performance consistency requires improvement.

B. RECOMMENDATIONS

1. That the nickel rich magnetostrictive plated wire be characterized in terms of the following fixed parameters:

   a) H_c (Coercive Force)

   b) H_k (Antrisotropy Force)

   c) B (Skew)

   d) α 90 (Dispersion)

2. That parameters to be characterized be evaluated against the following variables and combinations of variables.

   a) Tension

   b) Torsion

c) Temperature

d) Tension and Temperature

e) η_o (Magnetostrictive Coefficient)

f) Sensitivity of a sensor

3. That most applicable material characteristic be selected and tested as a 50- or 100-meter line.

4. That additional work be done on the logic to improve false target signal rejection.

Note: (1) Recommendations 1, 2, and 3, above, are primarily concerned with transducer sensitivity and consistency of performance in the field.

(2) Recommendation 4 recognizes that the use of more information features may well improve both detection and false alarm rejection of the improved transducer/electronic combination.

SECTION V

TECHNICAL DISCUSSION

A. SYSTEM DESCRIPTION

The P/M Line Sensor incorporates plated wire as a linear strain and magnetically sensitive element. Magnetic sensitivity of the present transducer has been minimized.

The strain sensitivity and transducer configuration actually detects earth deflection or deformation caused by an intruder. The P/M Line Sensor thus acts as a pressure sensor.

The present plated wire transducer consists of a 12, 000-Angstrom nickel-iron coating electrodeposited upon a 0. 010-inch beryllium copper wire substrate. The magnetization vector of the thin-film coating is driven about its rest position by a radio frequency carrier and, in the quiescent state, generates no net change in the output. An external magnetic field, however, tips the vector to one side, modulating the carrier with an analog of the external field change. The plated wire transducer thus acts as a magnetometer.

By altering the nickel-iron composition slightly, the film can be made magnetostrictive, or strain sensitive. Then, any strain in the wire caused by tension, bending, etc., will cause tipping of the magnetization vector from the rest position and also cause modulation of the carrier with an analog of the strain signal. Since pressure on the earth is converted to strain in the plated wire, the transducer acts as a pressure sensor.

The system block diagram is shown in Figure 1.

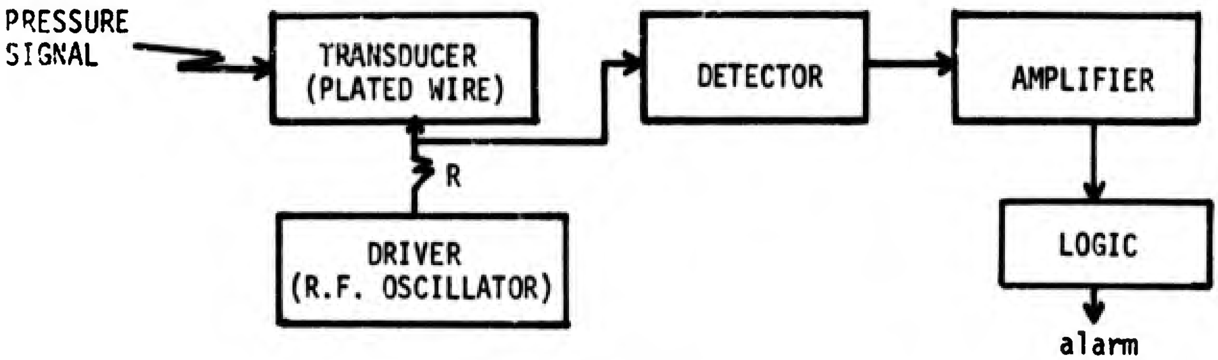


Figure 1. System Block Diagram

The transducer and the resistor R form a voltage divider as shown in Figure 2.

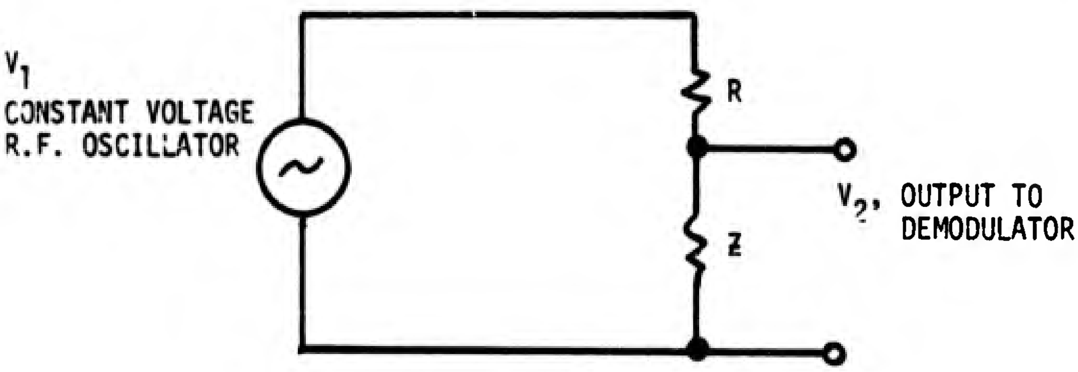


Figure 2. Basic Sensing Concept

The constant voltage source, V_1, drives the series resistance combination of R, a fixed resistance, and Z, the transducer impedance, which varies as the rest position of the magnetization vector is tipped causing modulation of the output voltage. This modulation is then detected in a demodulator and amplified to a level that can be utilized by the system logic. This logic determines if a signal "seen" by the transducer meets the established criteria to produce an alarm.

B. HARDWARE DESCRIPTION

The final hardware developed during this program consists of four components (transducers, electronics assembly, interconnect cable and battery pack) shown in Figure 3.

1. Transducer

Basically, the transducer is a coaxial cable with the plated wire utilized as the center conductor. The desired length is then terminated to obtain a standing wave of current which is as constant as possible along the transducer. This is necessary since the transducer sensitivity at any point is directly related to the current at that point.

Figure 4 is the transducer configuration. It should be noted that for the 50-meter transducer the second shield is not used. The second shield is used in a 100-meter transducer when the cable is terminated in a capacitor to provide a means of checking continuity of the transducer. Figure 5 is the finished transducer and cable termination.

Initial efforts to establish a working transducer utilized an iron-rich magnetostrictive film. However, due to magnetic property changes caused by stresses which were part of the field environment, several problems become apparent. One is the transducer sensitivity being directly related to the tension applied to the plated wire (Figure 6).

In relating sensitivity to tension, it would be desirable to know the material property/characteristic that causes sensitivity. This parameter is inductance and can be seen in the inductance versus tension curve for an iron-rich magnetostrictive coefficient of 30, 000 (Figure 7). If this inductance curve is differentiated with respect to tension, a curve shape matching the curve shape

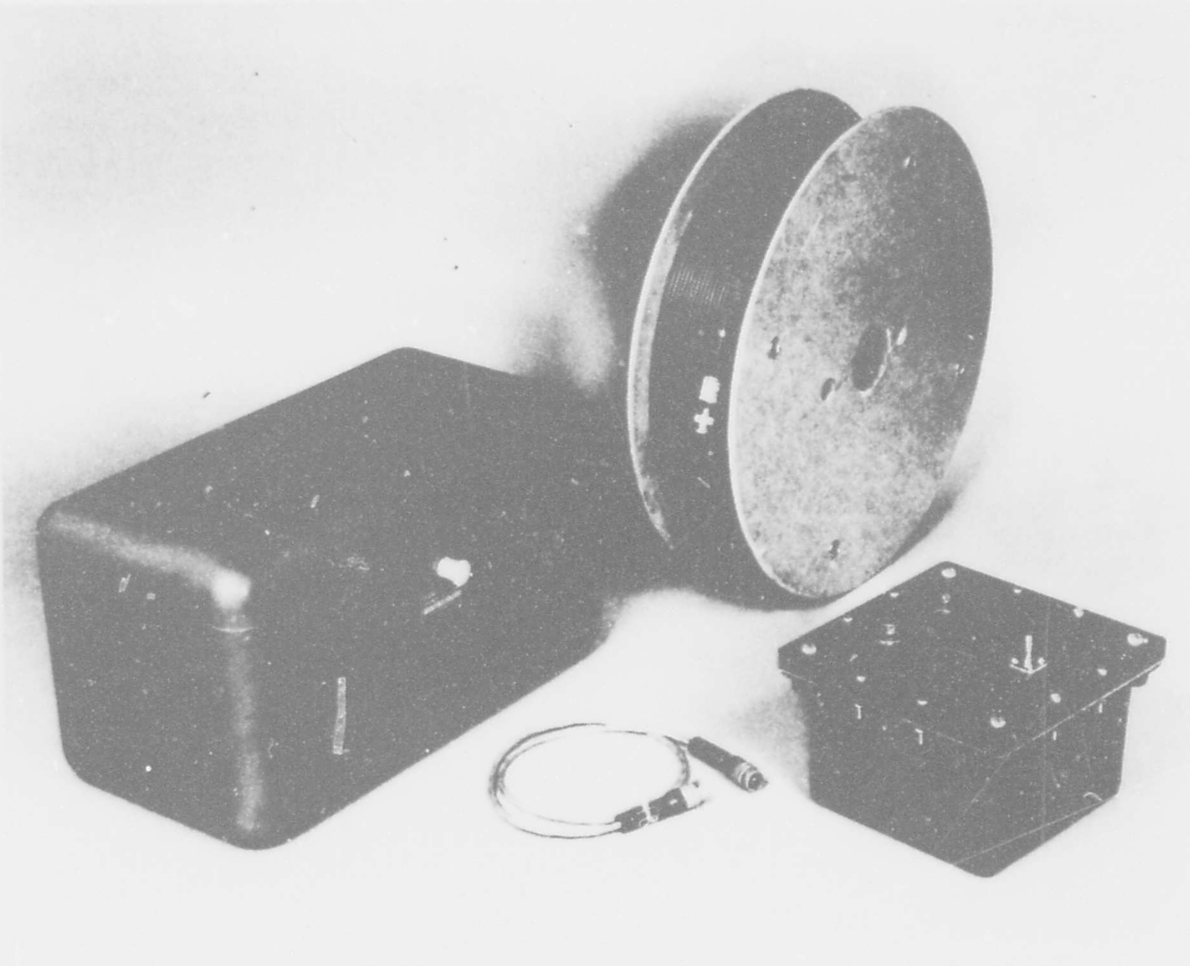


Figure 3. P/M Line Sensor Components

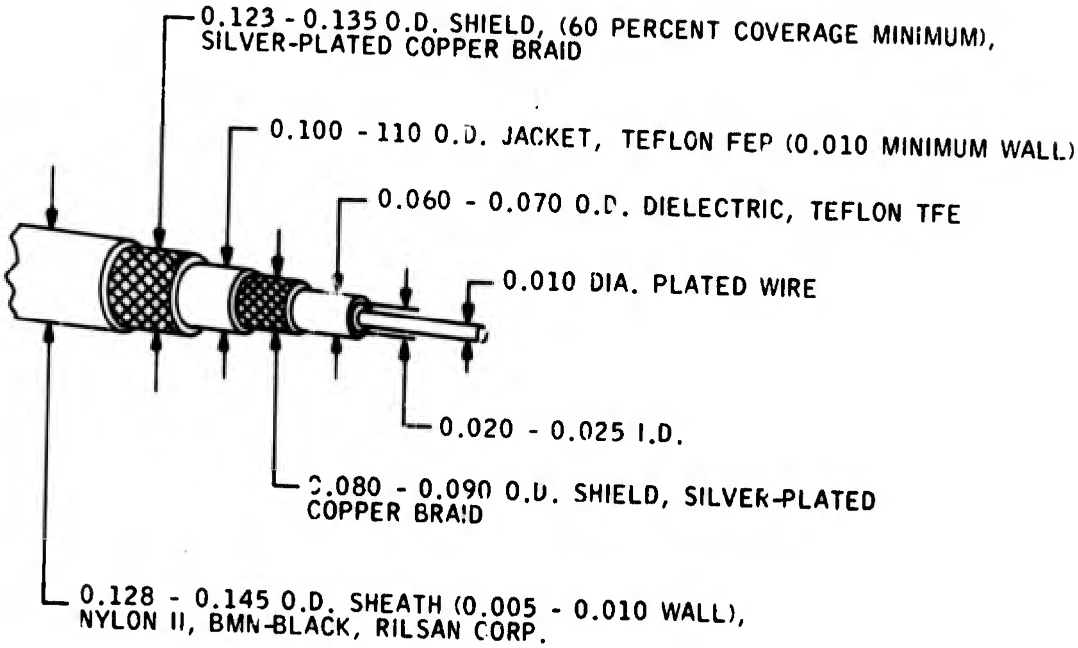
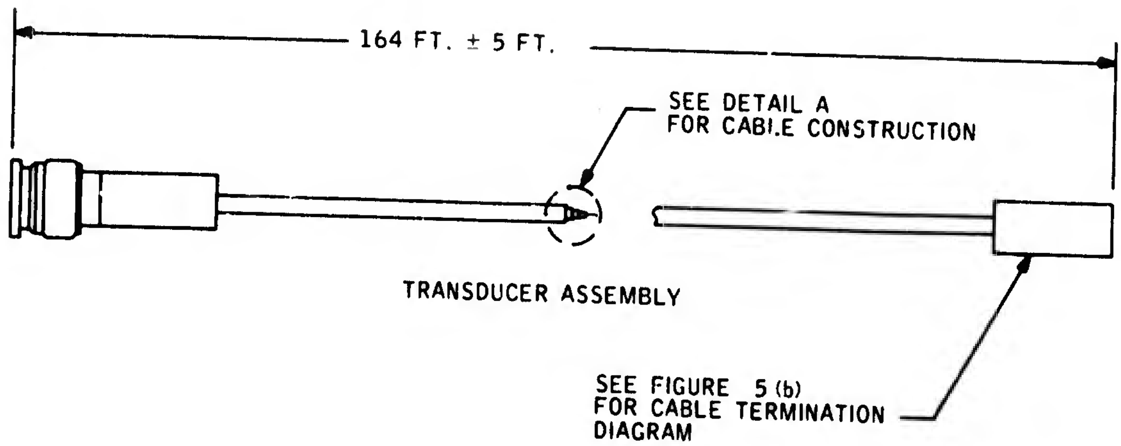
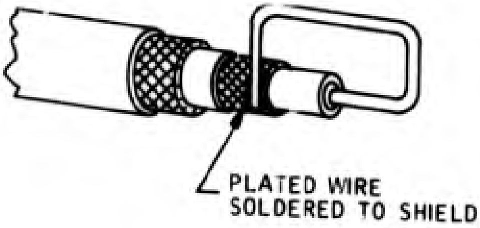


Figure 4. Plated Wire Line Sensor Cable Configuration



5 (a)



(CABLE TERMINATION)

5 (b)

Figure 5. Plated Wire Transducer Assembly

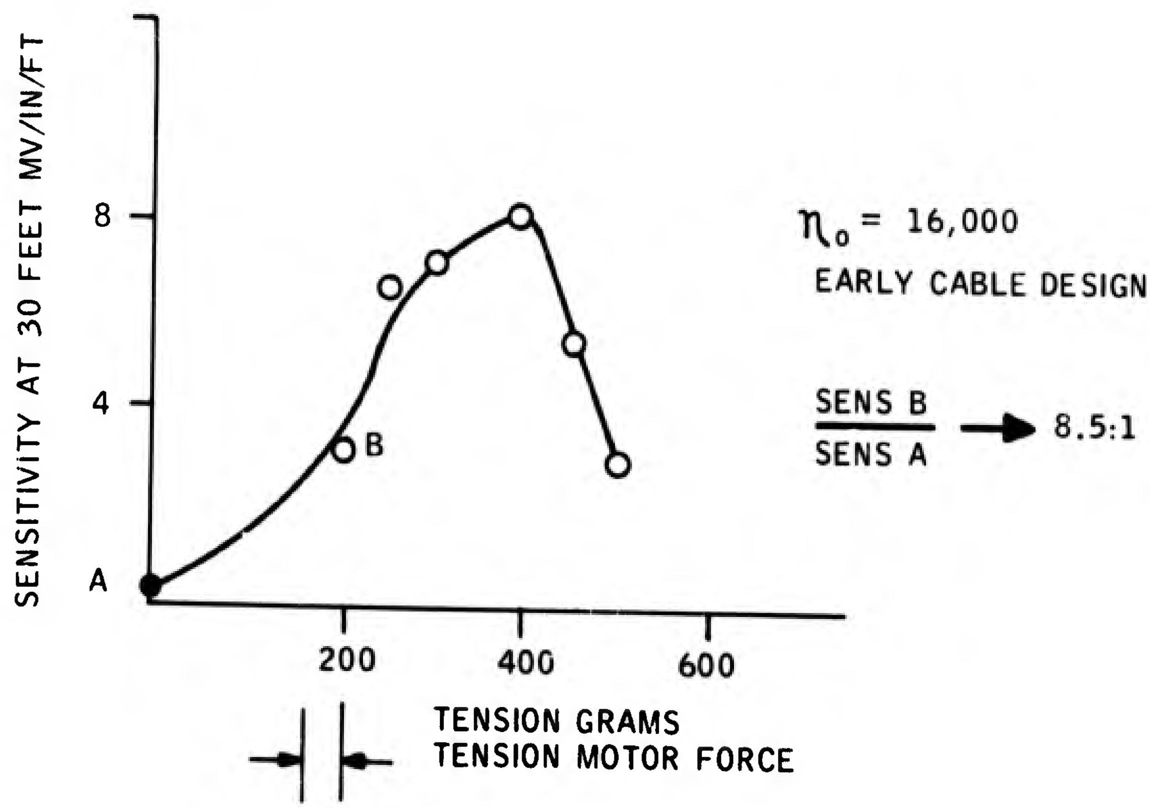


Figure 6. Measured Sensitivity Versus Tension

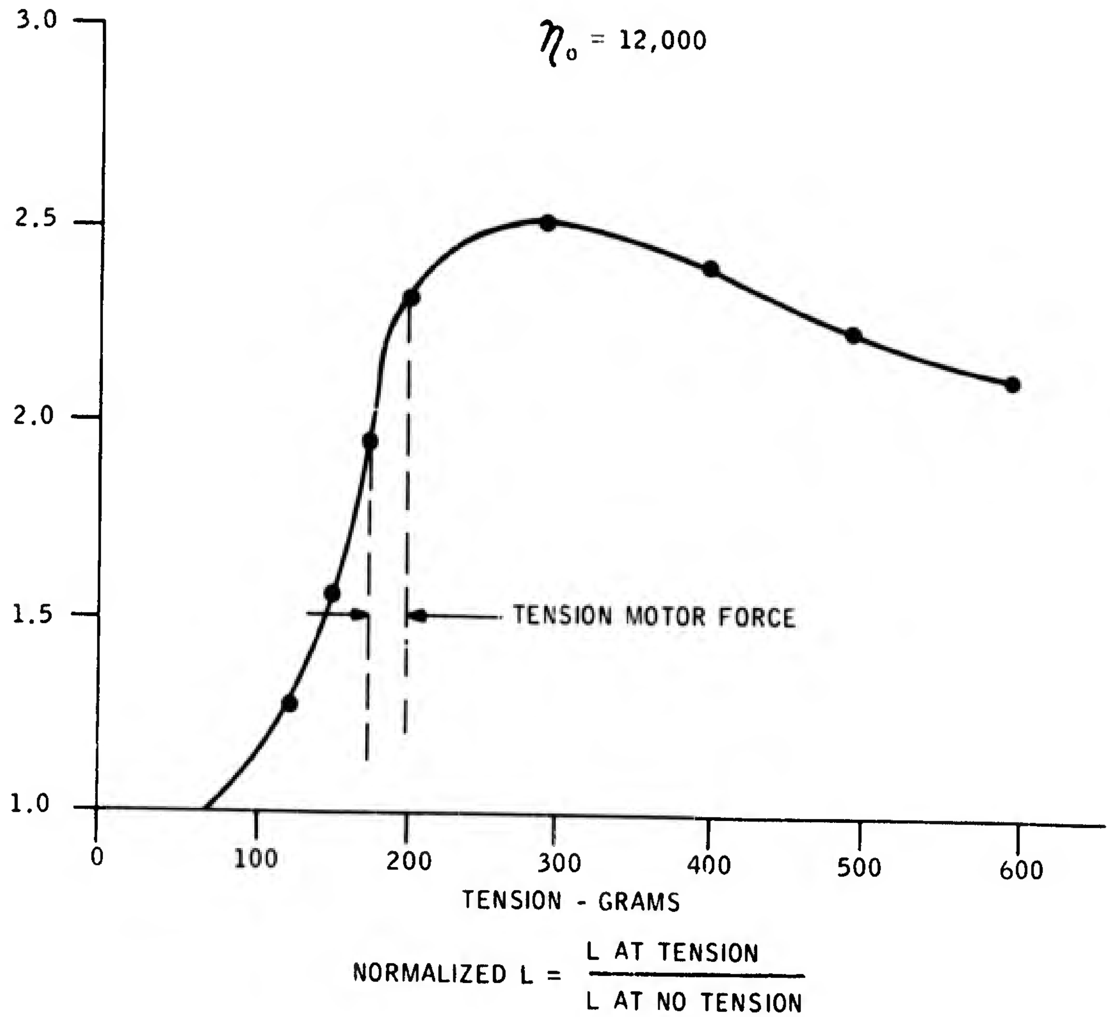


Figure 7. Plated Wire Inductance Versus Tension

of Figure 6 will be obtained. Since the drive supplied by the oscillator "sees" the effects of incremental inductance change, this is the basic sensitivity mechanism. However, it can also be seen from Figure 7 that, in order to maintain a consistent sensitivity, a constant tension bias must be applied to the plated wire.

A mechanical approach to the application of a constant tension bias was investigated. This method utilized constant tension motor to hold a bias tension on the plated wire within the limits indicated in Figure 6. This approach was not successful due to marked increase of the friction forces between the plated wire and the center dielectric of the transducer cable. This frictional force increased by greater than an order of magnitude from the laboratory to a field-deployment situation.

Due to the problems encountered with the sensitivity variations with tension bias, and instability problems related to handling, a change from an iron-rich to nickel-rich magnetostrictive material was recommended. Since the tension tends to rotate the magnetization vector away from the rest position with an iron-rich material, the opposite will be the case with nickel-rich material. This has proven to virtually eliminate sensitivity variations due to handling of the plated wire or the finished transducer. This has been noted by testing a transducer, reeling the transducer on a spool, unreeling the transducer, and retesting, performed with no observable change in sensitivity. A 50-meter line with nickel-rich material has been constructed and installed at the Honeywell Proving Ground (HOPG) with very favorable results.

The transducer operation is basically that of a transmission line. Sensitivity of the line at any point is directly related to the current at that point. This means that the standing wave of current on the transducer must be as uniform as possible along the line. This can be accomplished by proper termination of the transducer.

The basic standing wave of current on an open ended $\lambda/2$ transmission line is shown in Figure 8. This pattern can be changed by proper termination. Figure 9 shows a $\lambda/4$ line that is shorted. If this line is made $\lambda/8$, the standing will be as noted for the 50-meter line. This gives an exceptable current along the line to produce a workable transducer.

If a 100-meter or $\lambda/4$ transducer is required, the proper standing wave pattern can be obtained by a capacitive termination. This standing wave pattern is shown in Figure 10. Means of determining the capacitor value is shown in Figure 11.

The capacitor value is determined by the characteristic impedance of the line and frequency of operation. Impedance of the capacitor is equal to Z_o, at the frequency of operation. When the transducer is terminated with this value capacitor, the standing wave pattern will be as shown in Figure 10.

2. Electronics

The following discussion is a brief explanation of function and operational description for the electronic circuits used in the P/M Sensitive Line Sensor.

Voltage Regulator

Figure 12 is the schematic of the voltage regulator used to maintain a constant coltage reference and supply to the other circuits in the electronics assembly. The voltage regulator reduces the battery pack voltage, which ranges from 18.0 vdc to 12.5 vdc throughout the regulators useful life, to a constant 12.0 vdc ± 5 percent. The necessity for a stable voltage regulator is determined from two factors.

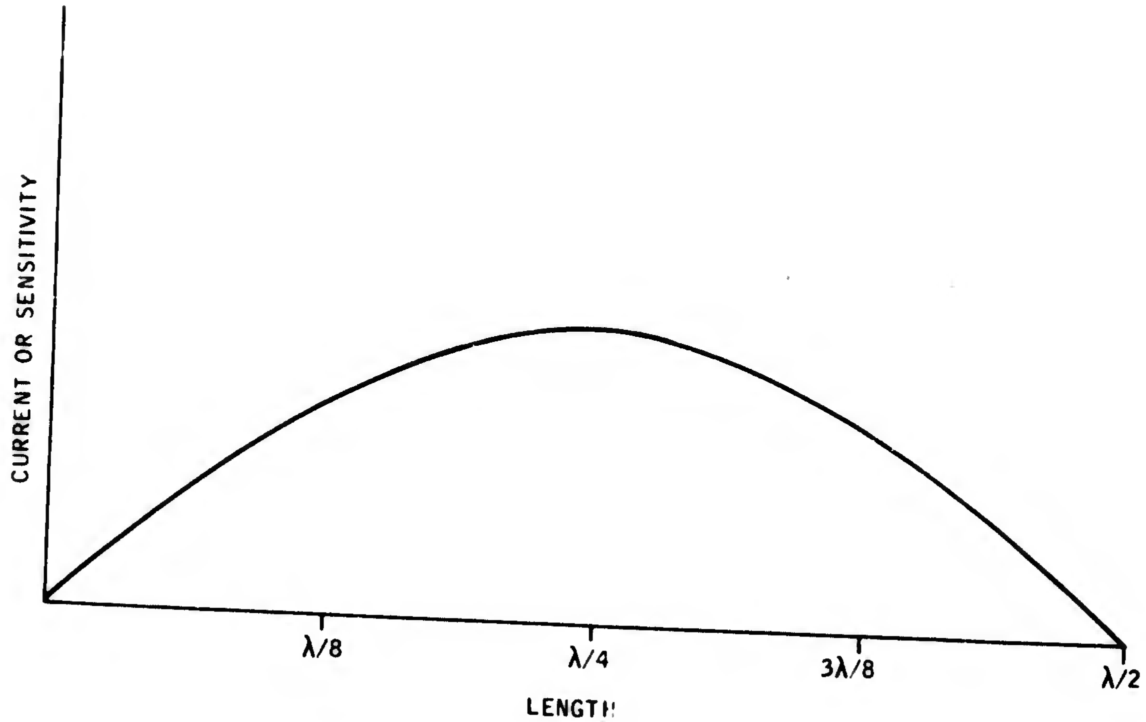


Figure 8. Standing Wave Current on a $\lambda/2$ Transmission Line

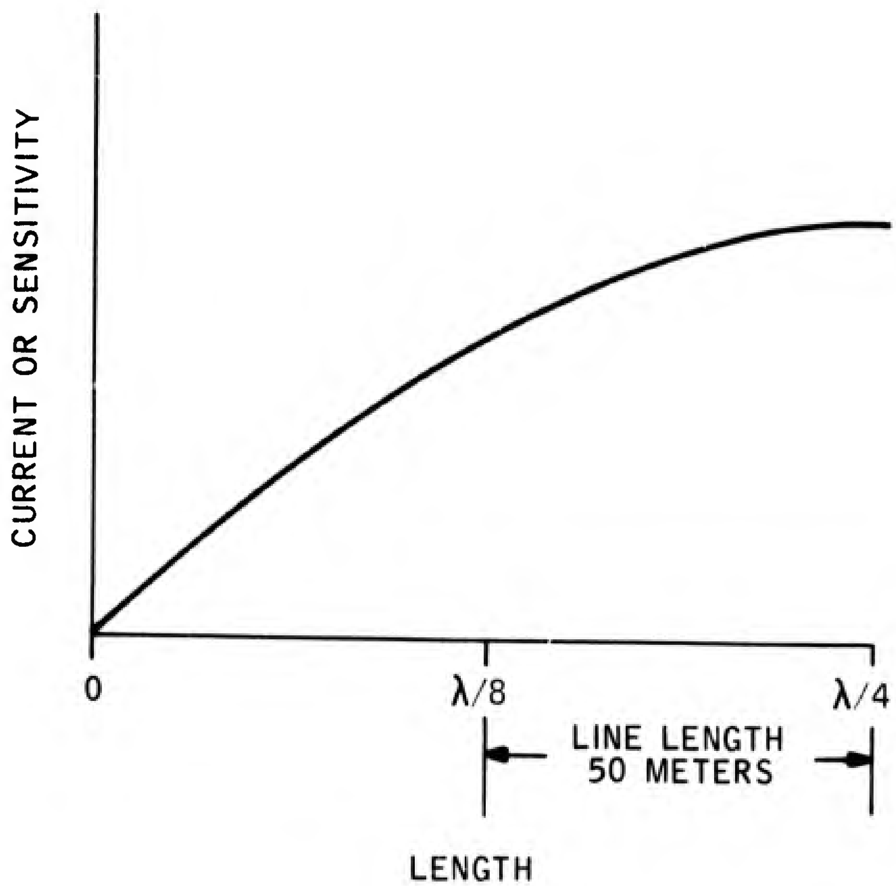


Figure 9. Standing Wave Current on a $\lambda/4$ Shorted Transmission Line

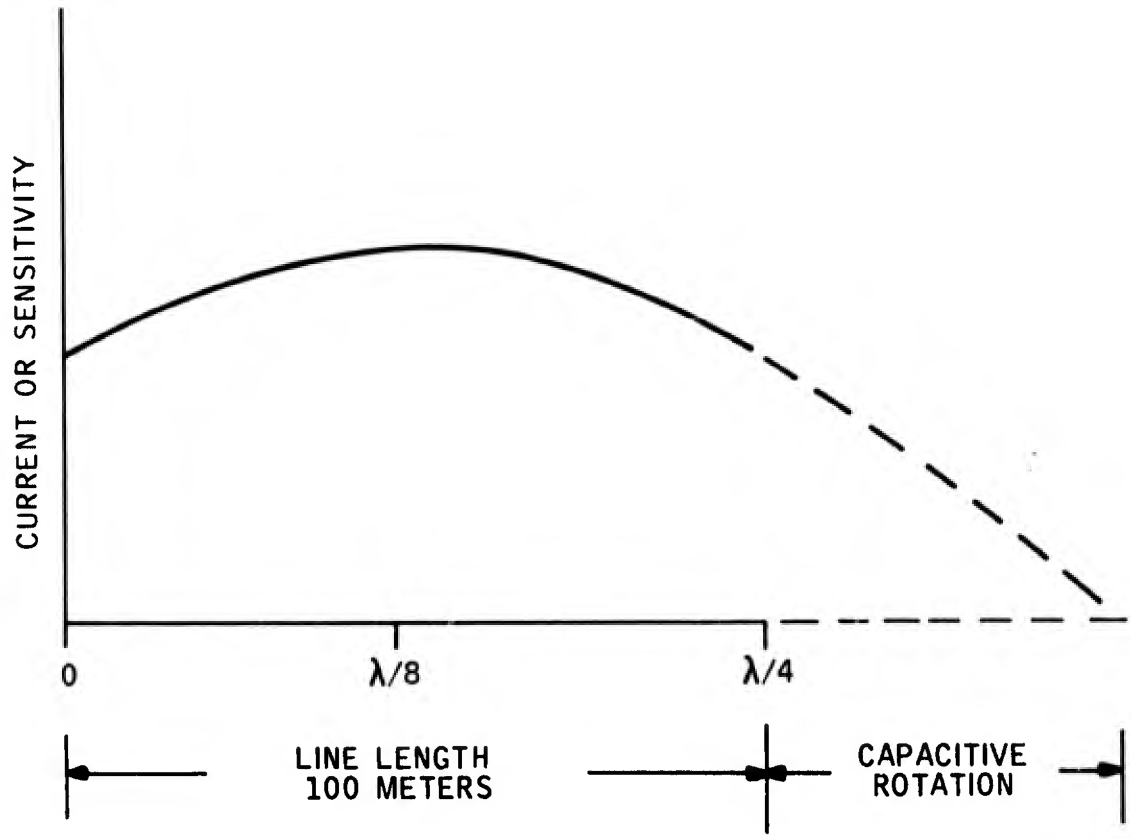


Figure 10. Standing Wave of Current on a $\lambda/4$ Transmission Line With Z_o Capacitive Termination

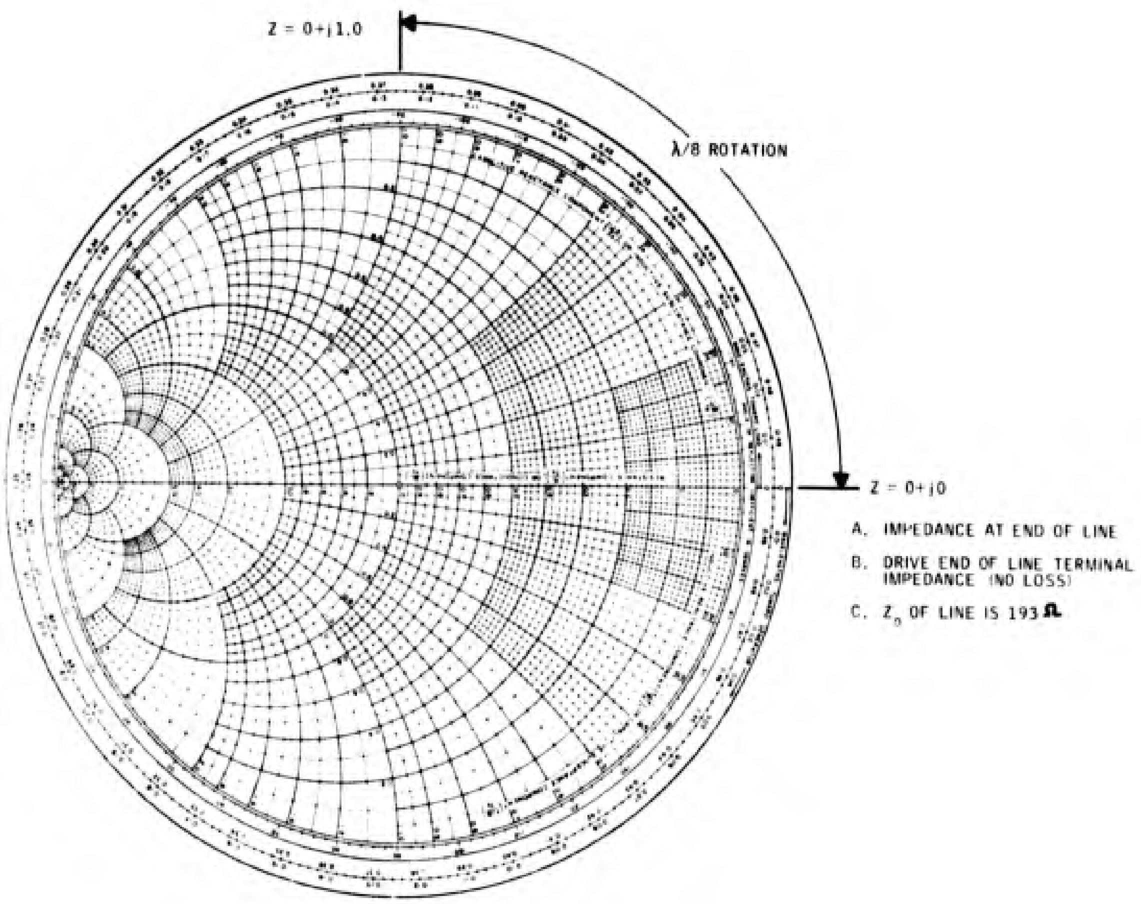


Figure 11. Analysis of Capacitive Termination for 100-Meter Line

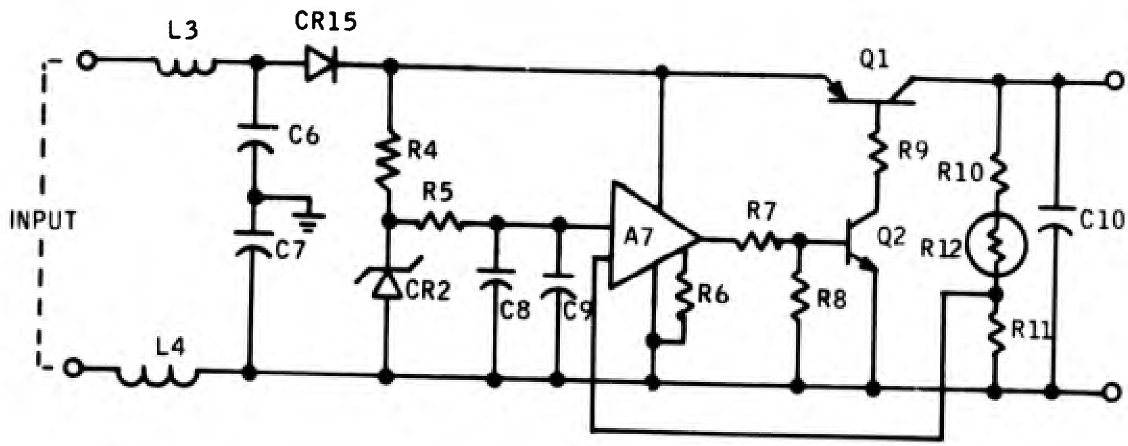


Figure 12. Voltage Regulator Schematic

1) A low noise ($\leq 10\mu Vp.p$) supply voltage is required to maintain system noise below the desired maximum equivalent input noise of 500 nv p. p.

2) A stable supply voltage is required to maintain a constant transducer drive over temperature and system life.

The voltage regulator operates by sensing the regulated output voltage via the temperature compensated divider network (R_{10}, R_{11}, & R_{12}) and comparing this voltage to a stabilized reference (CR_2) at the inputs of the amplifier A_7. The amplifier is a high gain operational amplifier which delivers the drive to the pass element Q_1 to turn it off or on, depending upon the loading.

Power Supply Splitter

Figure 13 is the schematic of the power supply splitter. The splitter is used to center tap the regulated supply voltage. This results in a plus and minus voltage referenced to a stable ground which can be used to bias the analog amplifier. The splitter functions as a voltage follower where the voltage across R_{32} with respect to the minus (-) input is obtained at the output of A_6. Amplifier A_6 is used as a current source and sink for B^+ and B^- respectively.

Oscillator/Line Driver

Figure 14 is the schematic of the oscillator/transducer driver circuit. The oscillator provides a constant frequency and amplitude deive voltage to the transducer. This oscillator is a basic Colpitts oscillator with the resonant tank circuit being comprised of L_2, C_4 and C_5. The transformer coupling to the transducer is used to provide impedance matching and thereby reduces the effects of loading on the oscillator. The frequency can be adjusted by tuning the value of L_2. The transducer, when excited, changes impedance and an amplitude modulated signal occurs between R_1 and the transducer.

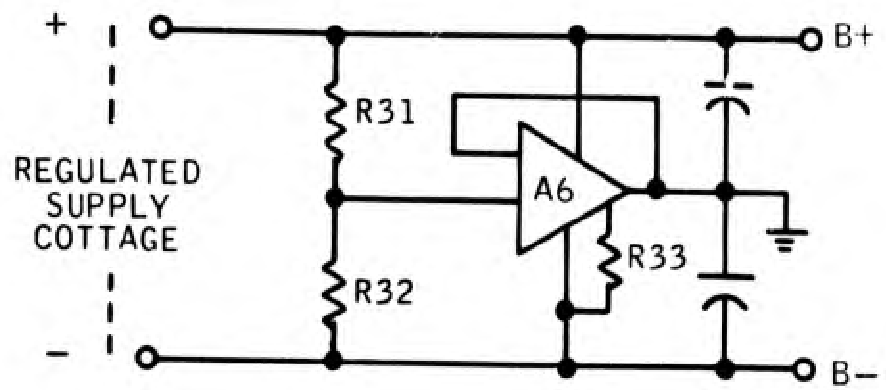


Figure 13. Power Supply Splitter Schematic

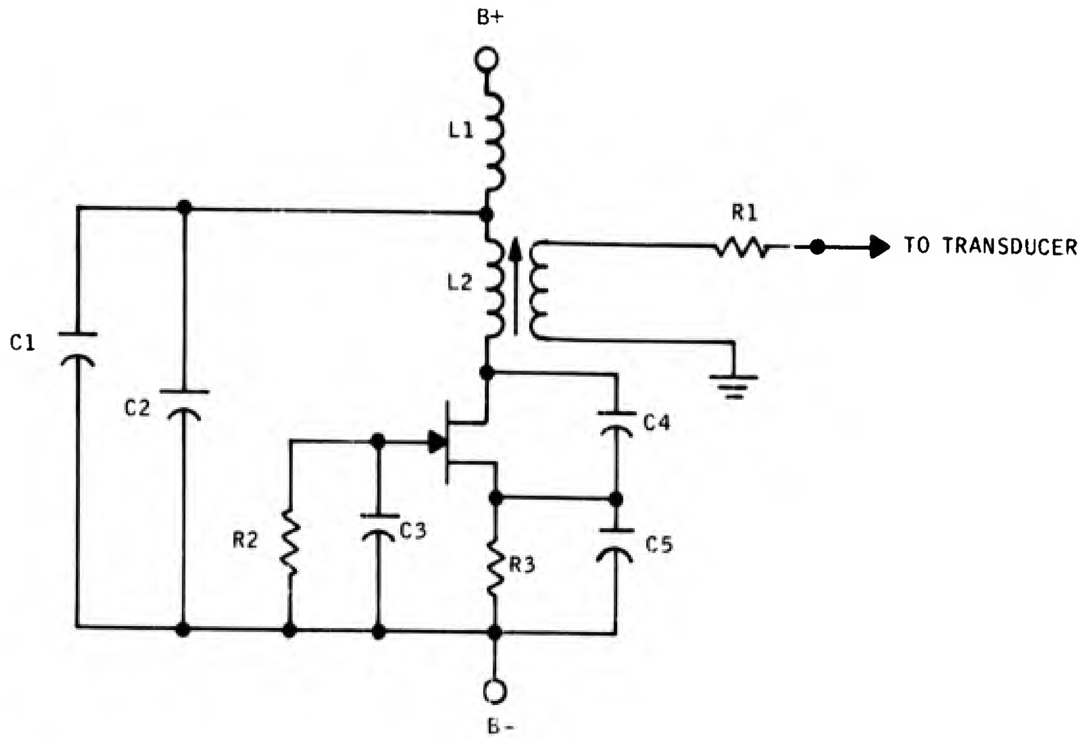


Figure 14. Oscillator/Line Driver Schematic

Amplifier

The amplifier performs two primary functions:

(1) Amplification of the signal from the transducer

(2) Bandpass filtering of input signals.

Figure 15 shows the schematic of the amplifier. The voltage gain is 100 db at a center frequency of 1.0 Hz and rolls off at 60 db/decade. The -3 db frequencies are 0.25 Hz and 2.5 Hz. Signals from the transducer are in the form of amplitude modulation of the a-c signal driving the transducer. Amplitude demodulation is accomplished by CR_1 and C_{11} and a resultant d-c signal is established at the input to the amplifier. The low noise performance of the amplifier is accomplished by using a discrete transistor differential amplifier pair at the input. Additional gain is obtained by using two operational amplifiers, A_1 and A_2. Bandpass filtering of the input signal is accomplished with three individual R-C filters breaking at 0.1 Hz and three individual R-C filters breaking at 5.0 Hz.

Zero Crossing Detector

Figure 16 shows the schematic of the zero crossing detector circuit. Input to the zero crossing detector is derived from the amplifier output. A lack of output from the amplifier is characterized by a low frequency ($\approx$ 1.0 Hz) noise signal of very low amplitude. This signal is directly coupled to the noninverting input of operational amplifier A_3 which is used as a high gain comparator. The inverting input of A_3 is heavily filtered so that it does not follow the input signal except for long-term drift in d-c input levels. The inverting input of A_3 is utilized as a low frequency floating reference. As the input swings plus and minus with respect to ground, A_3 output swings from B^+ to B^- at the frequency of the input signal.

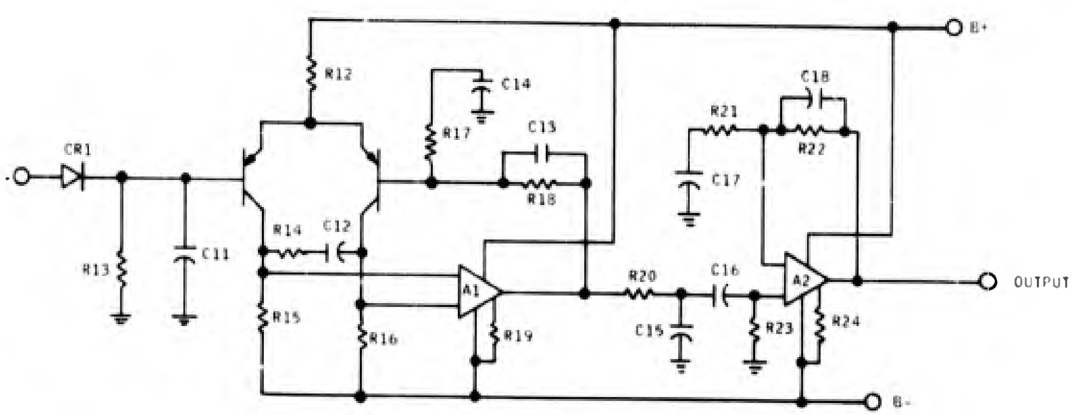


Figure 15. Amplifier Schematic

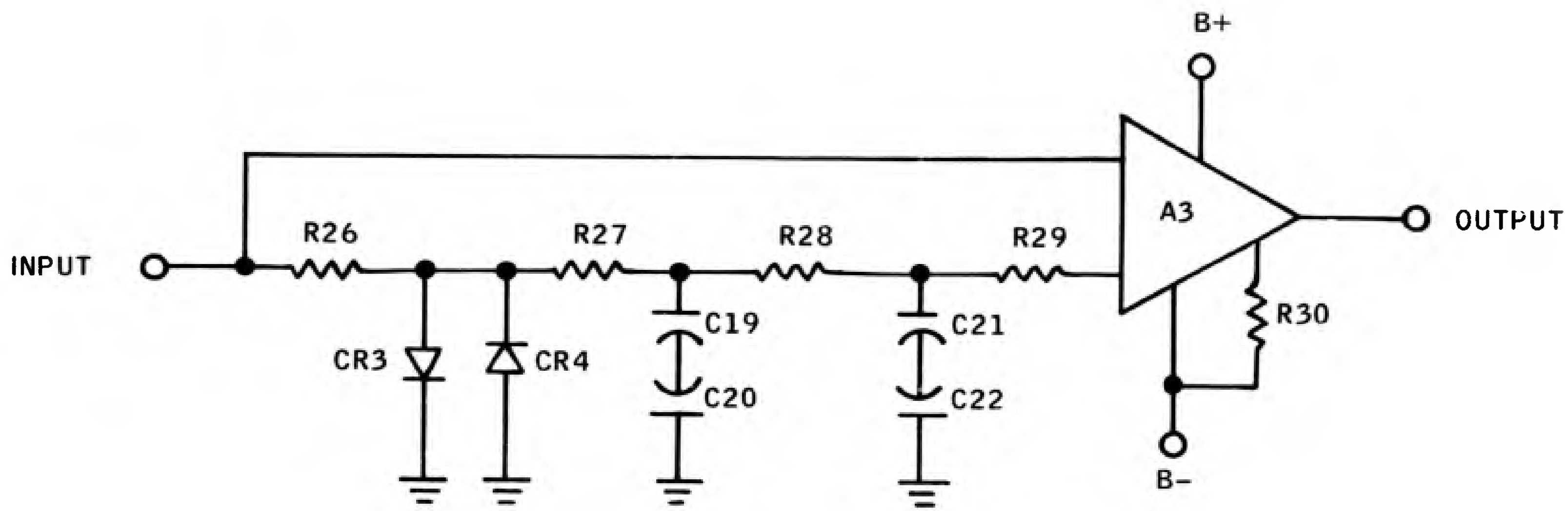


Figure 16. Zero Crossing Detector Schematic

When a target signal is applied to the input, the output for A_3 pegs to one side or the other and the rate of switching is drastically reduced. The reduction or lack of switching at A_3 output is used to define a target signal in the decision logic.

Level Detector

Figure 17 is the schematic of the level detector circuit. This circuit monitors the analog amplifier output and produces an output signal upon a target signal which exceeds a preset threshold voltage. Operational amplifier A_4 is a positive signal level detector and A_5 is a negative signal level detector. The two outputs are combined in an "OR" gate via diodes CR_5 and CR_6. Threshold levels are high enough to reject normal background noise signals but low enough to detect even the smallest target signals. The level detector output is used as an "enable" function only in the decision logic.

Logic

Figure 18 is the schematic diagram of the logic circuit used to discriminate between target signals and nuisance signals. The logic consists of five basic functional blocks.

(1) Clock-free running pulse generator used to establish a sample period.

(2) Decade counter - counts zero crossings during the sample period.

(3) Level detector one shot - provides an "enable" pulse of approximately twice the clock period upon being excited by the level detector output.

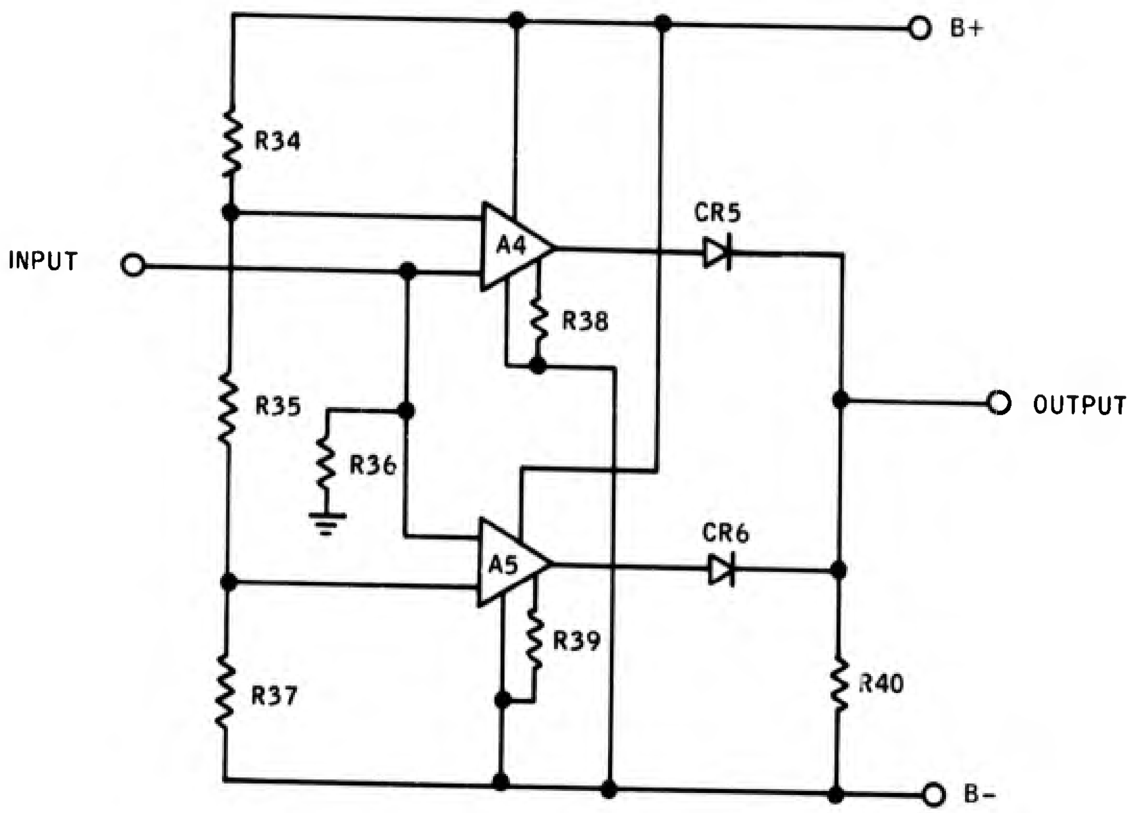


Figure 17. Level Detector Schematic

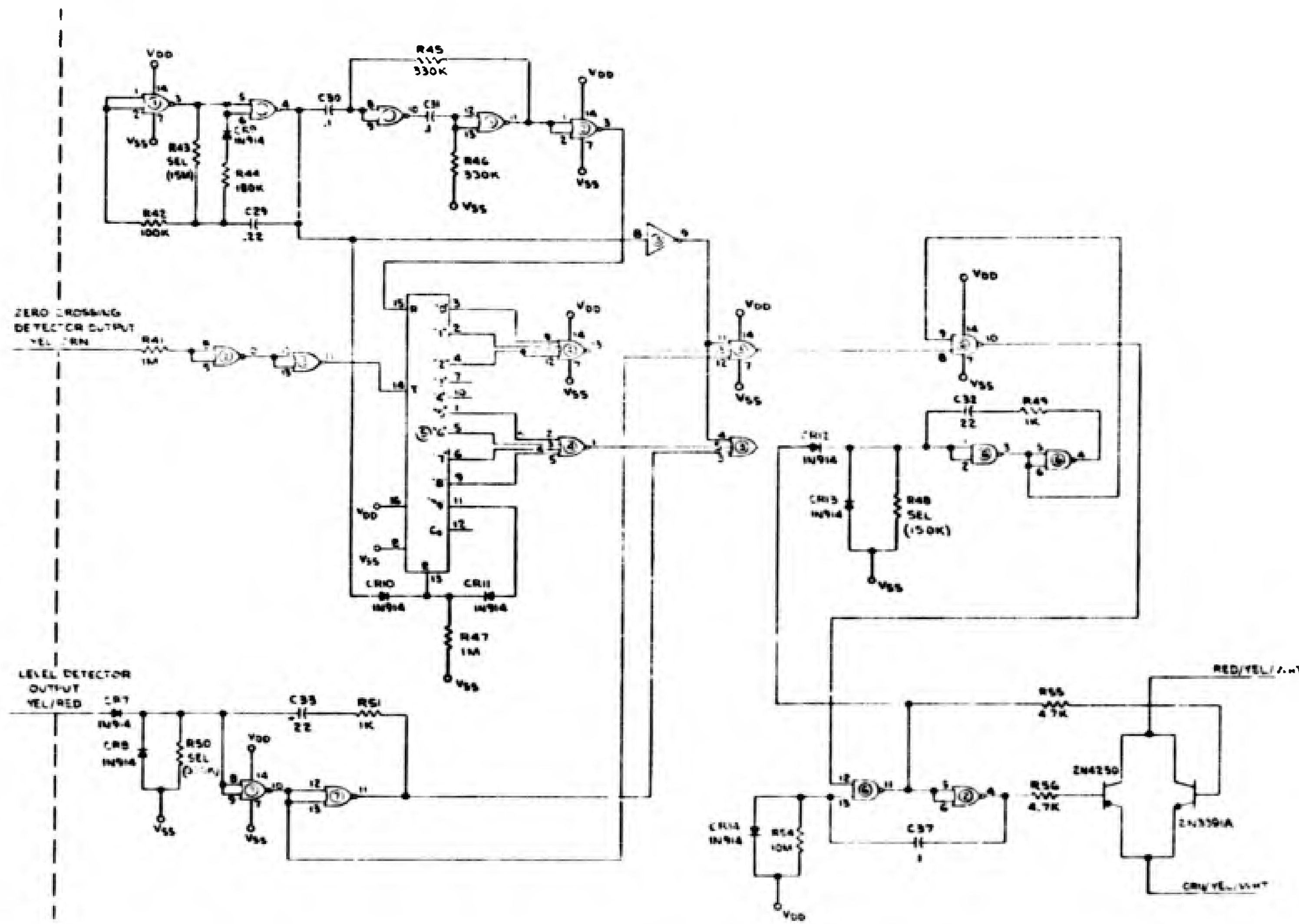


Figure 18. Logic Schematic

(4) Output one shot - provides an output pulse of 500 msec to the output switch.

(5) Output switch - a bilateral switch capable of carrying up to 100 ma d-c.

The decade counter is toggled by the output of the zero crossing detector. At each clock pulse the counter is reset back to "zero." During a nontarget excited period the zero crossing counts will exceed "2" per clock period. All counts greater than "2" are ignored by the logic. When a target signal is generated, the zero crossing counts will decrease to a "0", "1", or "2" count. Also, the level detector one shot is excited. At the next clock pulse, if the counter is in the proper state and the level detector one shot is "hi", an output pulse will be generated. This pulse triggers the output one shot and provides a 500-sec base drive signal to the bilateral switch.

3. Interconnect Cable

The interconnect cable is fabricated from a shielded twisted pair cable and two four-pin connectors. This cable provides the interconnect between the battery pack and the electronics and is approximately 3 feet long. The shielded twisted pair cable is hard-potted into the connector to provide rigidity and a watertight seal. See the Appendix for the wiring diagram.

4. Battery Pack

The battery pack supplies the energy necessary to drive the transducer and the electronics package. This pack consists of 18 number 6 magnesium cells and 20 silicon diodes. Two parallel sets of nine cells provide an output voltage of approximately 15.5 vdc. The silicon diodes are used to provide a "soft" fail; one or more cells failing does not seriously affect the output voltage. Batteries and diodes are housed in an aluminum case backfilled with a polyurethane potting. See the Appendix for the battery pack schematic.

C. HARDWARE PERFORMANCE

Performance of the deliverable hardware is limited by performance of the transducer. Throughout the development program, various transducer configurations and/or characteristics were analyzed with a prototype electronics known to give superior performance.

Figure 19 shows performance of a 50-meter transducer installed at HOPG. This transducer was installed at approximately 10 inches depth. It should be noted that the transducer performance was very good except near the connector end. Data of Figure 19 was taken with 6 inches of frost in the ground.

Figure 20 shows the performance at a single point with and without a 6-inch hay soil covering. Apparently, addition of the hay does not greatly affect signal magnitude but does appear to lower the signal frequency content. It should also be noted that the data of Figure 20 was taken at a point of low sensitivity on the line.

A 24-hour false alarm test was performed on a 100-meter transducer buried at the Honeywell Proving Grounds. Prior to and following the 24-hour test period, the system was tested every five meters over its entire length to verify an operational system. Two false alarms were recorded during the test. Cause of the alarm is unknown.

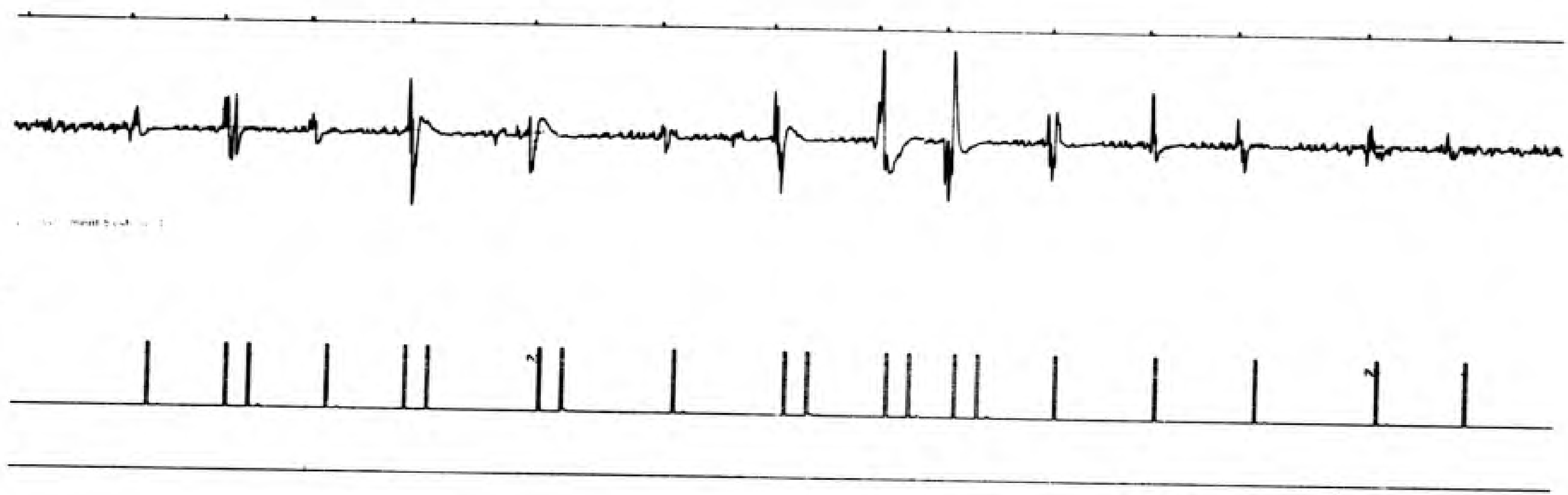


Figure 19. Fifty-Meter Line Performance When Installed at 10-Inch Depth and With 6 Inches of Top Ground Surface Frozen

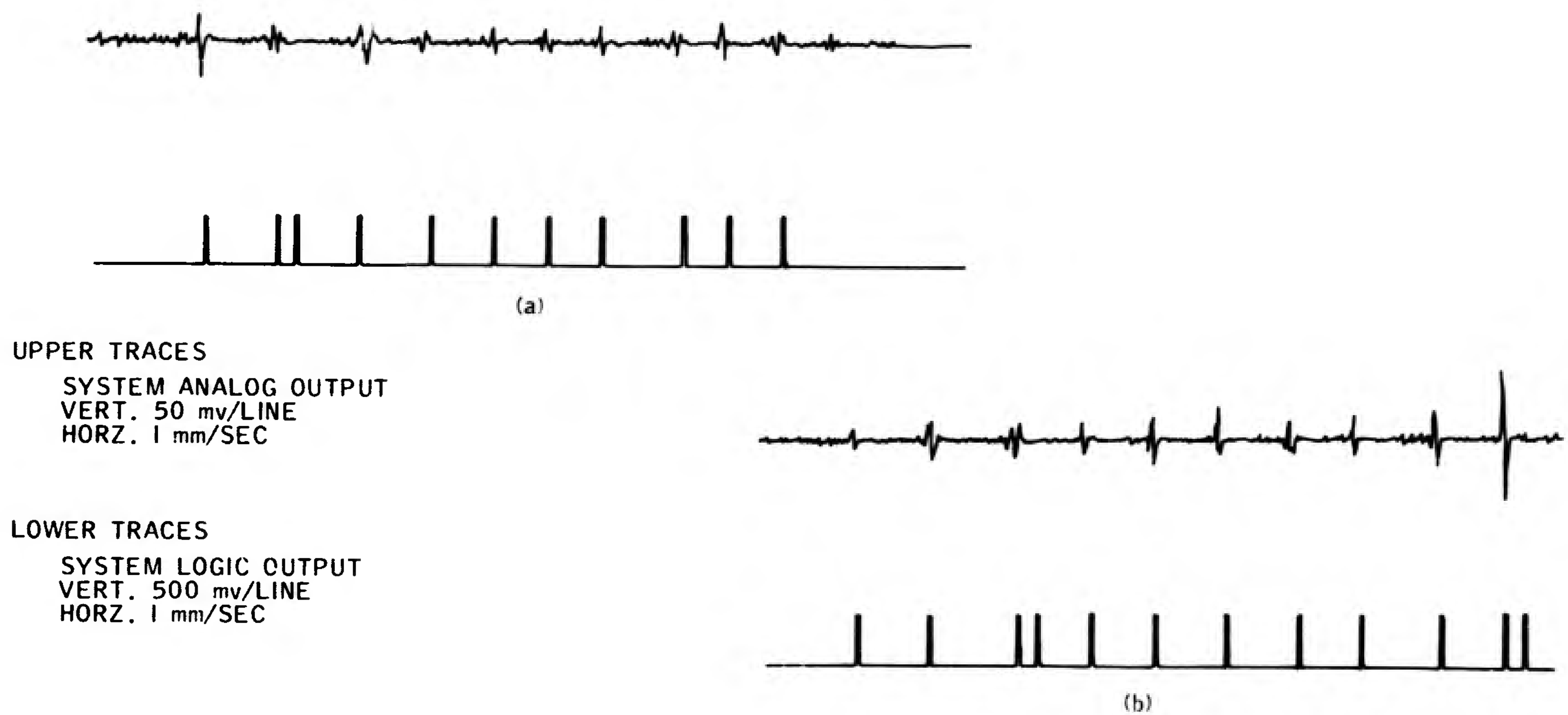


Figure 20. Response of 50-Meter Line to Single Human at 10 Feet

D. PLATED WIRE PROPERTIES DEVELOPMENT

1. Test Program

It was recognized that a considerable improvement in overall P/M line sensor signal-to-noise ratio would be required for successful accomplishment of the system's objectives.

One of the best means of improving signal-to-noise ratio is to increase the signal level. The plated wire properties task was designed to improve the gage factor (sensitivity) of the sensing wire through manipulation of the plating formulation and processing steps. Five wire properties were selected as key parameters of the transduction process and a variation matrix setup. The wire utilized in prior Honeywell Independent Development programs was used as the control against which all other samples were evaluated.

Each sample was tested for deflection in the test fixture (Figure 21). A 4-foot section of wire was inserted in a piece of special hollow coaxial cable and electrically connected as a shorted quarter wavelength transmission line. The center span of the test fixture (12 inches) was deflected a known distance and the sample output recorded. A deflection gradient (inches deflection per inch of span) voltage constant was thus determined and all wire samples compared for sensitivity.

Each sample was also tested for response to tension in the test fixture (Figure 22). A 1-foot section of wire was damped in the coaxial fixture (which was operated as an open quarter wavelength transmission line) and gram weights applied to strain the wire axially. The d-c response of the wire versus tension was thus established.

The two tests were undertaken because the deflection test is analogous to field inputs and thus representative of actual performance. It is a difficult

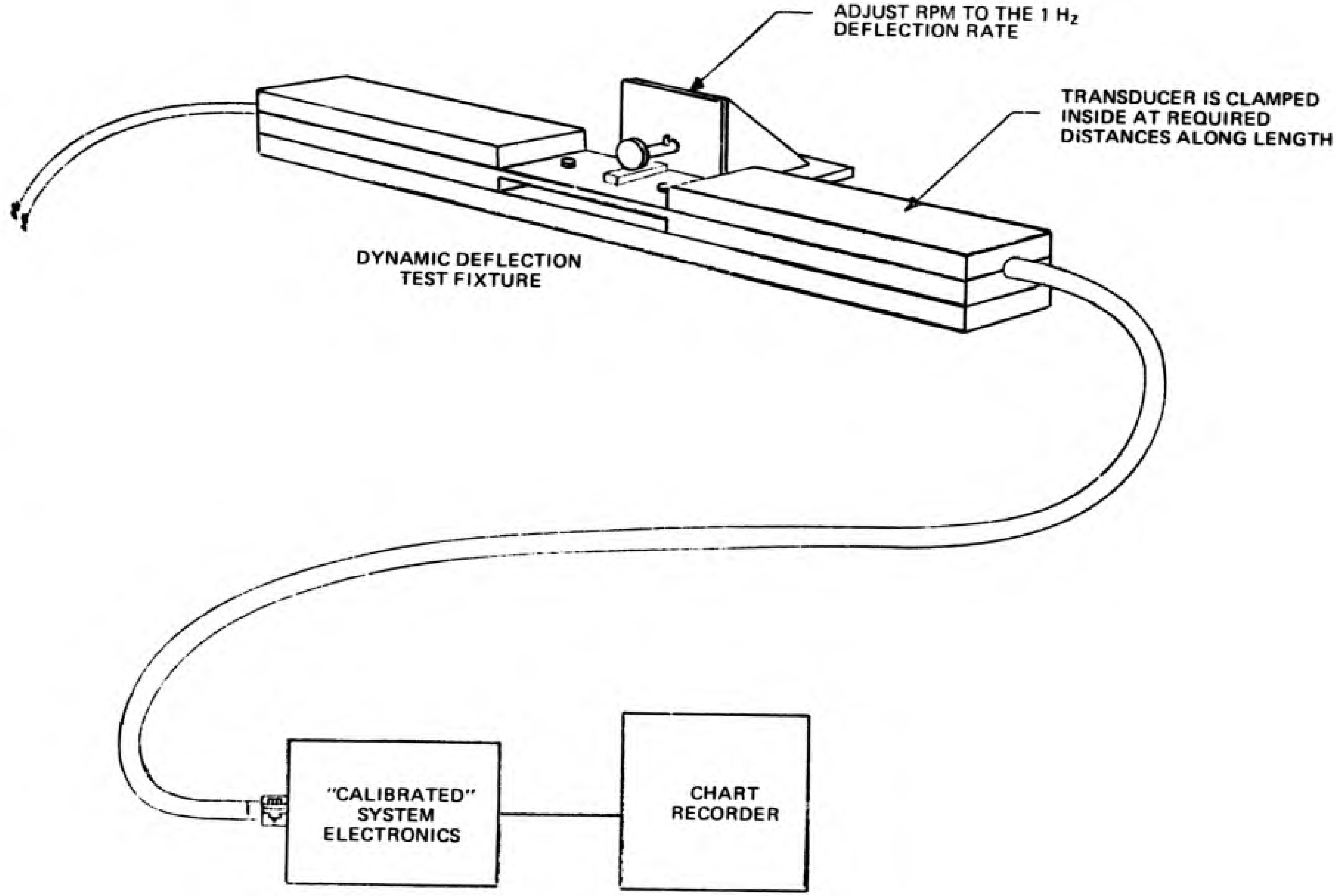


Figure 21. Transducer Sensitivity Dynamic Deflection Test

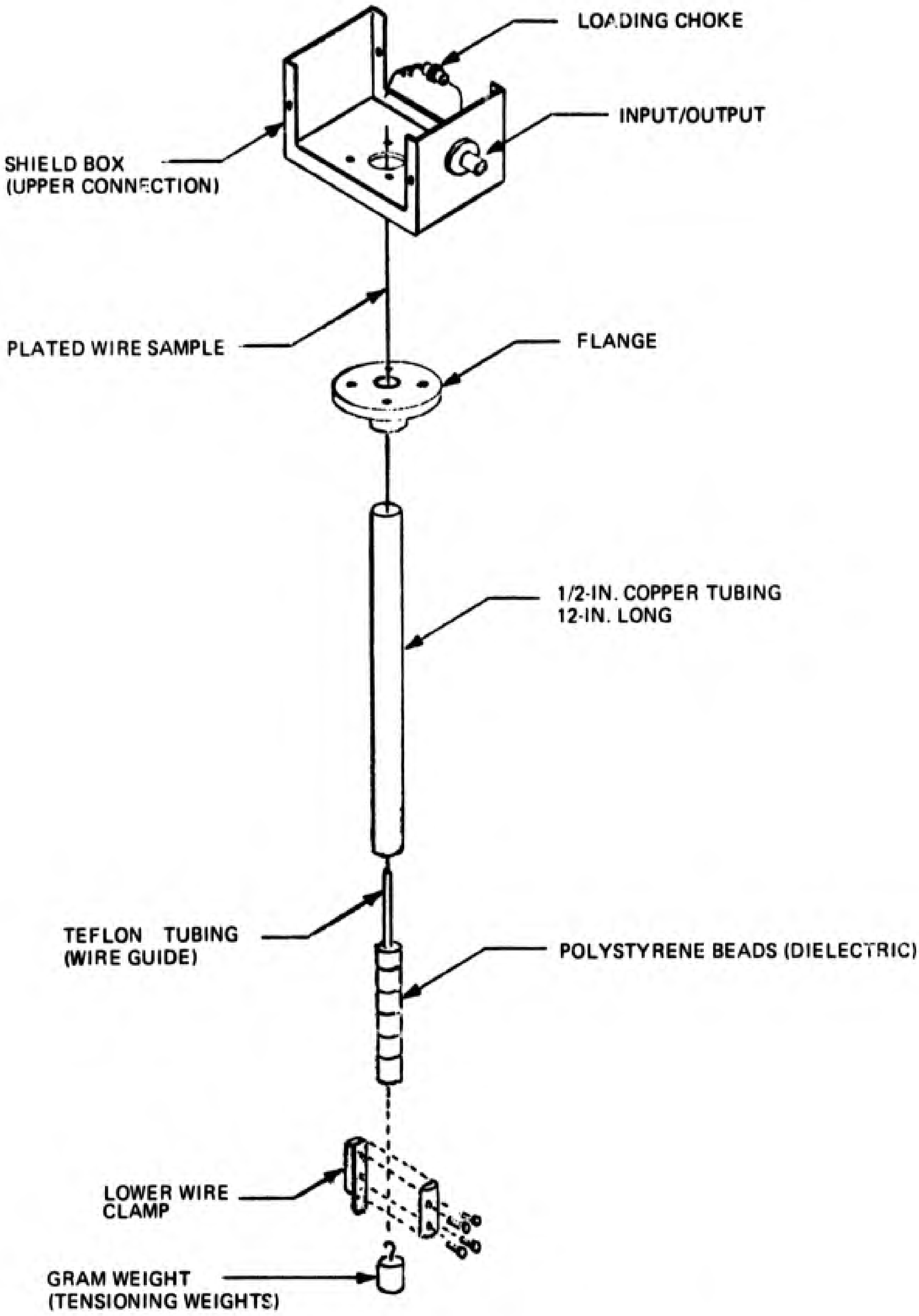


Figure 22. Tension Test Fixture

test to perform, however, and not well suited to rapid testing. The tension test is a simple test that could be performed on-line during wire manufacture. The two tests were thus performed simultaneously to determine the amount of correlation between the two methods.

The properties and their variations are shown in Table I. In each case all parameters, except the variable one, were held constant within the limit of the fabrication process. (There was, unfortunately, more variation in the fixed parameters than one would have desired, the larger variation being tolerated to keep within fiscal limitations.) Test results are plotted in Figures 23 and 24.

2. Test Results

a. Coercive Force (H_c) Variation -- Increasing coercive force resulted directly in a decrease in deflection sensitivity for positive magnetostriction samples. Negative magnetostriction samples showed a slight increase in sensitivity. It was also noted that increasing H_c required increased drive power.

b. Skew (β) -- Increasing skew (both positive and negative) reduced deflection sensitivity for positive magnetostriction samples and increased sensitivity for negative magnetostriction samples.

c. Magnetostriction (η_o) -- Increasing positive magnetostriction initially caused deflection sensitivity to go to zero, then increase in the negative direction. Increasing negative magnetostriction increased sensitivity (from zero), peaking at 17 - 18 KO_e, then falling to zero from the peak.

d. Film Thickness (t) -- Deflection sensitivity changed slightly as film thickness increased. Neither positive nor negative magnetostriction was

TABLE I. PROPERTY VARIATIONS

PROPERTY	SYMBOL	MAXIMUM	MINIMUM	CONTROL
COERCIVE FORCE	H_C (Oe)	10	4.8	4.8
SKEW	β (DEG.)	5	1	2
MAGNETOSTRICTION	η_c	+ 20,000	-20,000	+ 7,500
PLATING THICKNESS	t (A)	15,000	8,000	12,000
DIAMETER	d (IN.)	0.010	0.005	0.005

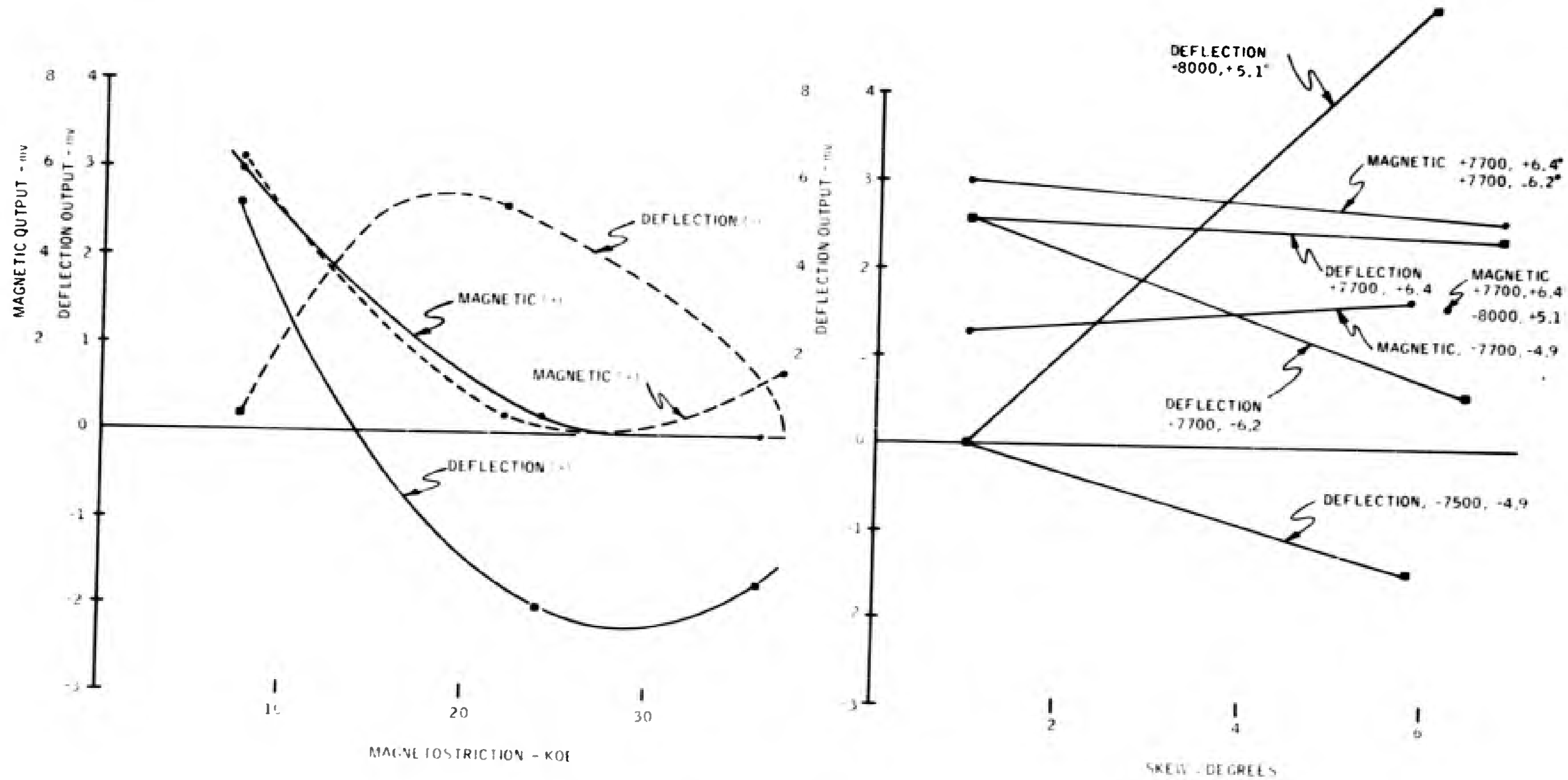


Figure 23. Plated Wire Magnetostrictive Properties

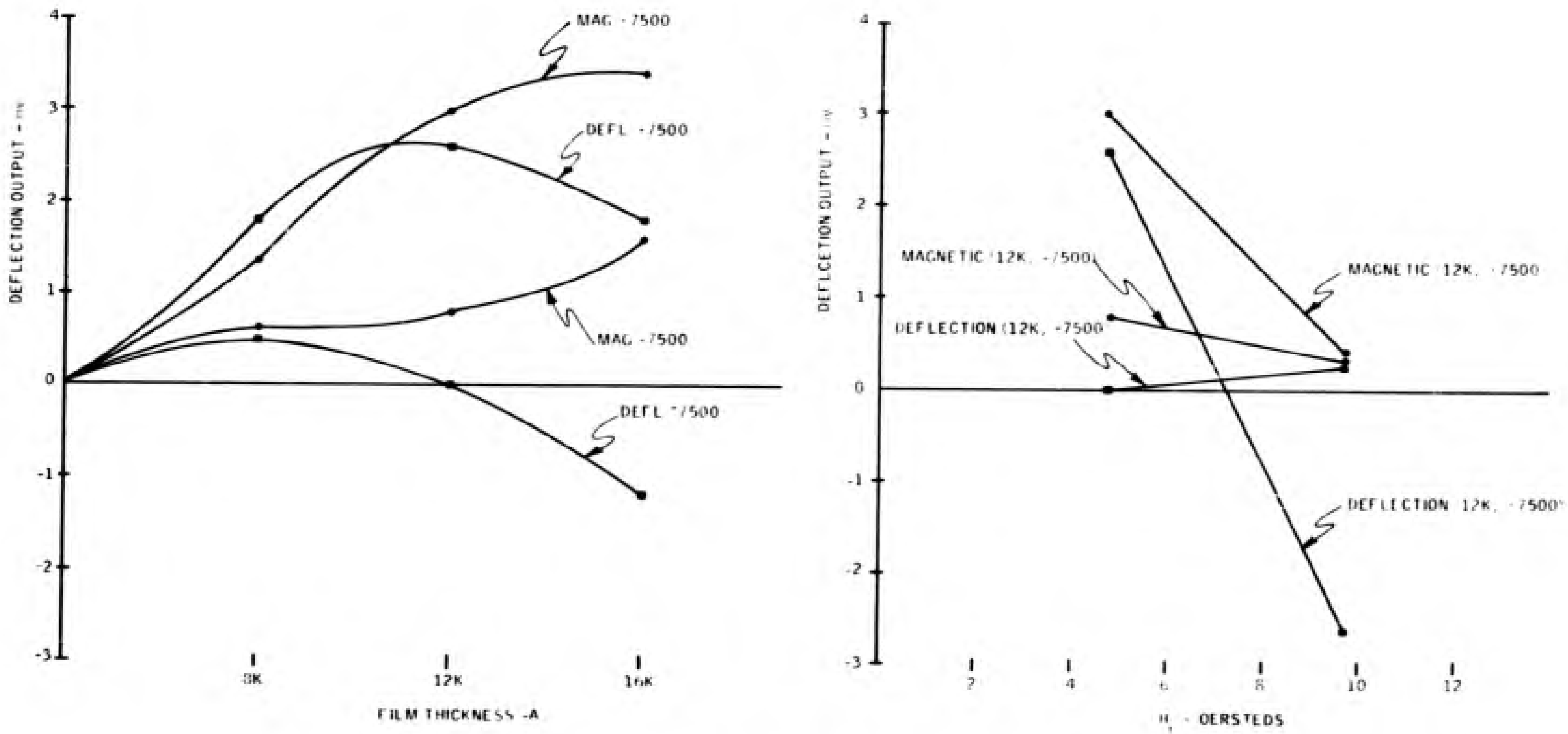


Figure 23. Plated Wire Magnetostrictive Properties (Concluded)

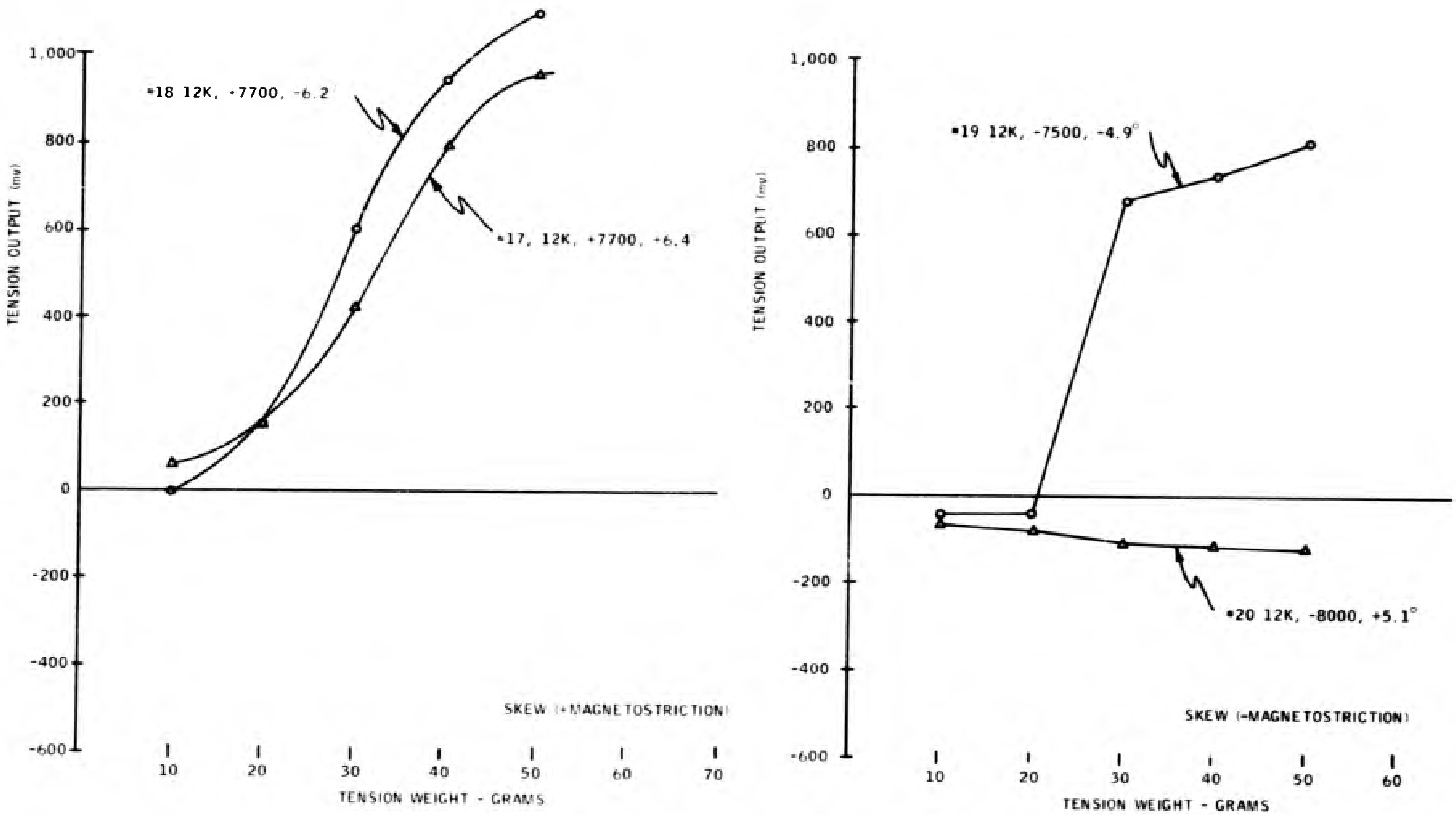


Figure 24. Plated Wire Tension Properties

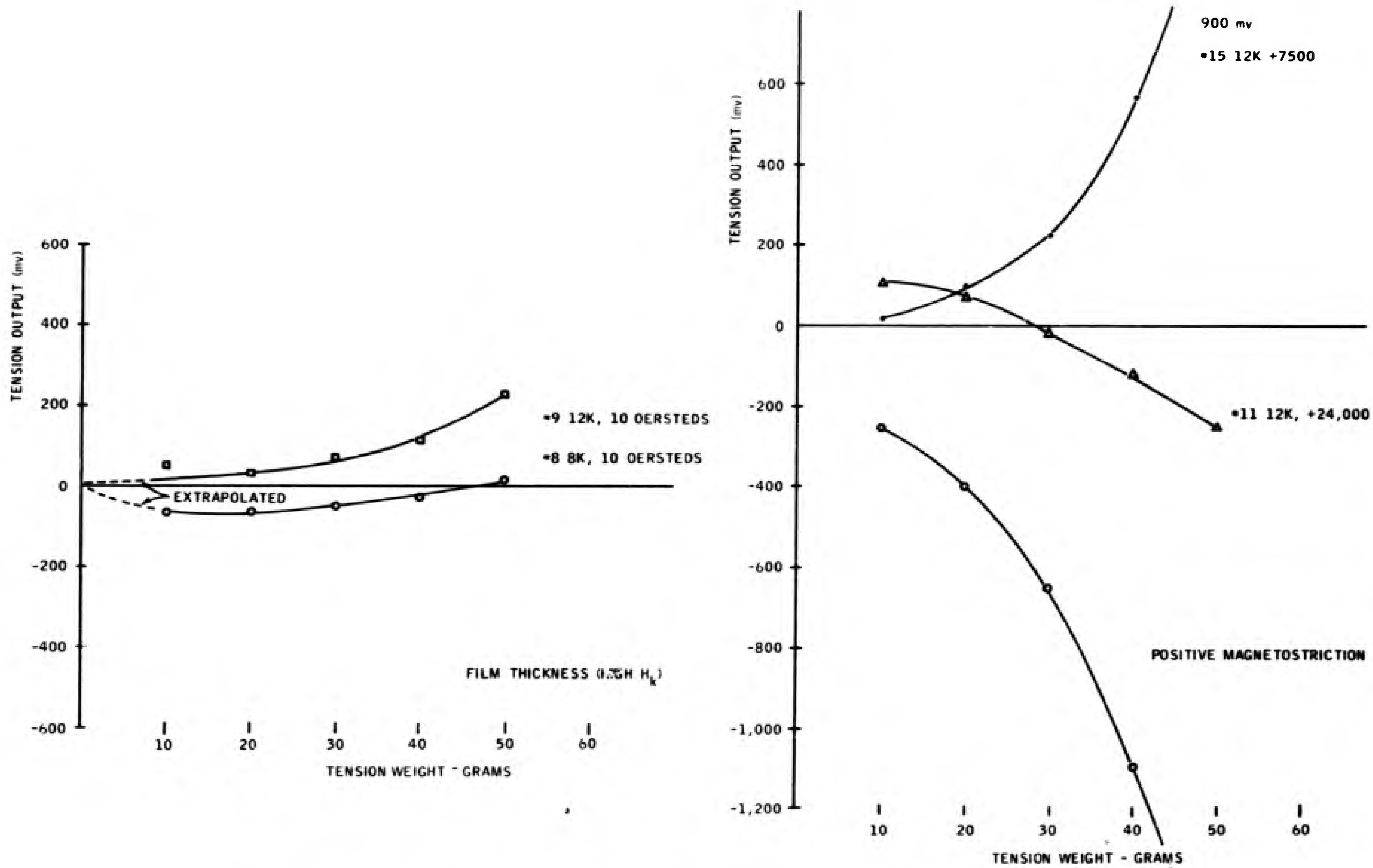


Figure 24. Plated Wire Tension Properties (Continued)

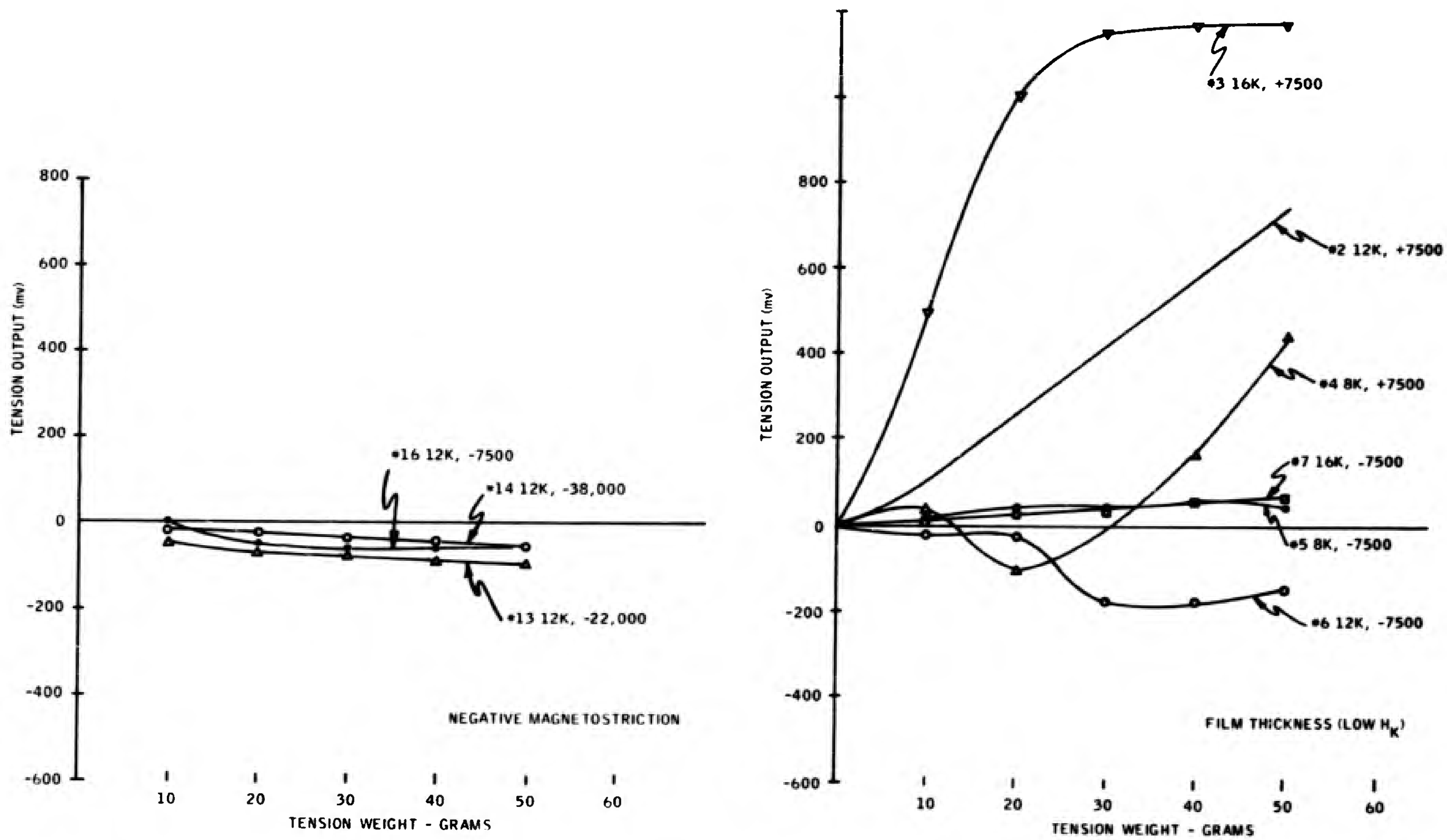


Figure 24. Plated Wire Tension Properties (Concluded)

appreciably affected. Drive power, however, increased directly as film thickness increased.

3. Conclusions

The highest sensitivity would be realized from the following two compositions:

a) H_c = 4.50e, β = +5.1 degrees, η_o = -17,500, t = 12KÅ

b) H_c = 4.50e, β = 1 degree, η_o = +27,500, t = 12KÅ

The deflection sensitivity of a) was indicated to be better by a factor of 2:1 over b). The composition of b) was chosen, however, due to its superior magnetic influence rejection. The higher positive magnetostriction composition demonstrated a nearly zero sensitivity to magnetic signals. This aspect is particularly important in terms of influence separation when the line sensor is utilized as a combination pressure/magnetic sensor.

The desired properties were combined into a 5-mil wire sample and into a 10-mil wire sample. It was noted that the hgiher magnetostriction in the larger diameter (10 mil) wire could cause skew to increase, thus reducing the net sensitivity improvement. To test this hypothesis, several 10-mil wire samples were produced with a range of magnetostriction for testing. Test results of these samples are illustrated in Figure 25. Table II summarizes the property development results.

E. CONTINUOUS TRANSDUCER FABRICATION

All transducers fabricated prior to the P/M Sensitive Line Sensor Program had utilized either standard coaxial cables (with center conductors stripped

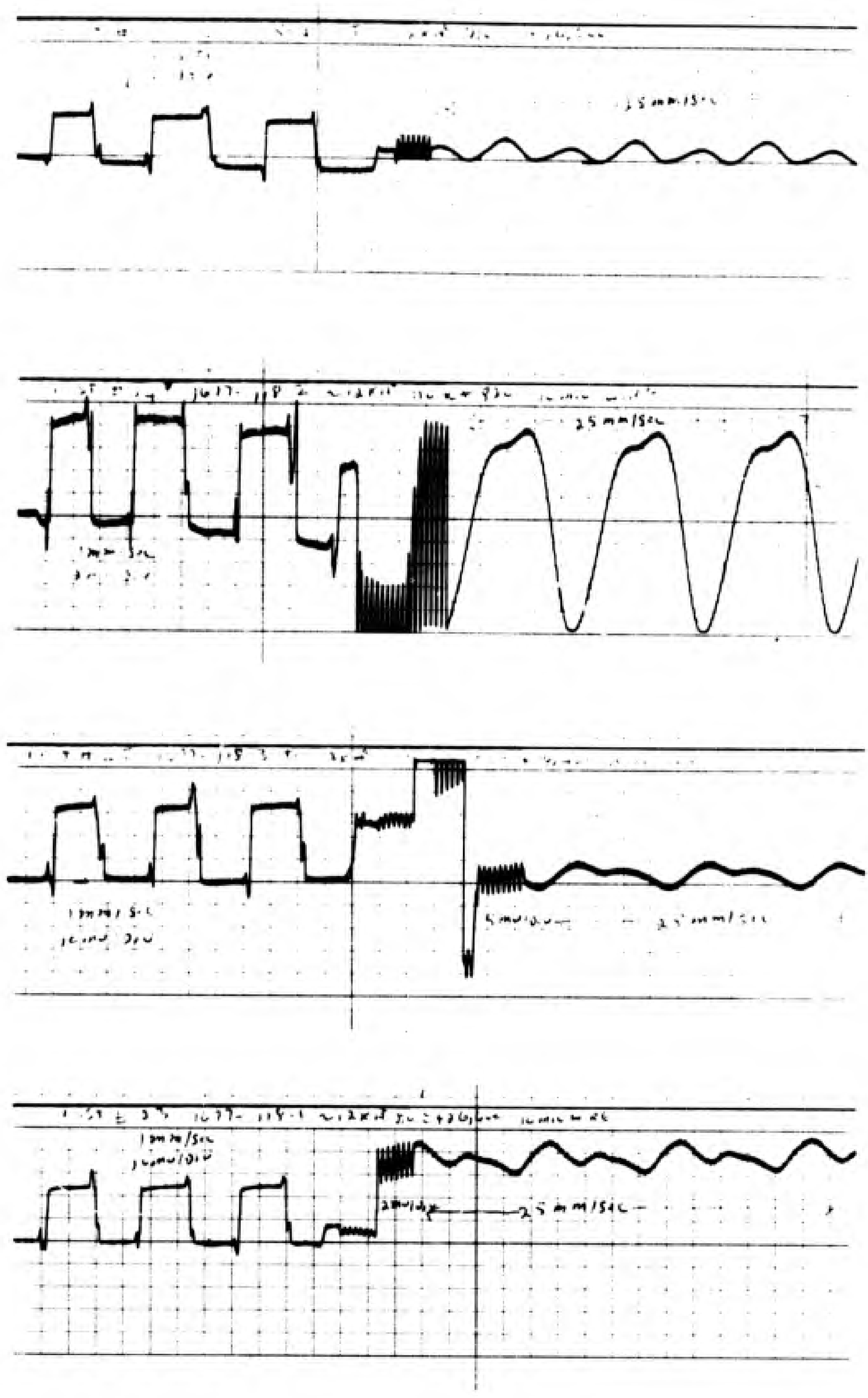


Figure 25. Ten-Mil Plated Wire Sensitivity

TABLE II. PROPERTY IMPROVEMENT RESULTS

	PROPERTIES					DEFLECTION TEST OUTPUT-mv (0.002 IN/IN)	MAGNETIC TEST OUTPUT (mvpp)	RELATIVE IMPROVE-MENT DEFLECTION/ MAGNETIC
	H_c (oe)	λ_o K	β (DEG.)	t (KÅ)	d (IN)			
CONTROL	4.8	7.5	<1	12	0.005	3.0	7.0	1.0/1.0
SECOND PHASE	4.8	27	<1	12	0.005	10.0	10.0	3.3/1.4
FIRST 0.010	4.8	8	<1	12	0.010	4.6	10.0	1.5/1.4
PROTOTYPE	4.8	27	<1	12	0.010	12.0	1.9	4.0/0.27
	4.8	16	<1	12	0.010	17.0	3.0	5.7/0.43

out) or a special hollow dielectric (precursor) coaxial cable. It was estimated that 100 meters represented the maximum length of wire that could be pulled into the precursor cable and that any longer transducers would require different techniques. The continuous transducer fabrication task was set up to develop a process to obtain long continuous transducers with the sensing wire built into the transducer during manufacture.

Hi Temp Wires Incorporated was selected to develop the continuous transducer fabrication process. It was soon determined, however, that the teflon cover's extrusion temperatures would exceed the sensing wire curie point and destroy the usefulness of the wire. It was determine that maintaining a current in the wire during processing would alleviate the degrading effects of the high temperature. However, at the same time, a process was developed which eliminated the transducer's exposure to the higher temperatures.

As Figure 26 illustrates, the extruded dielectric was replaced by a braided dielectric containing 24 strands of 0.014 FEP monofilament. The dielectric was braided around the sensing wire as a discrete tube whose diameter was designed to be 10 to 15 mils larger than the sensing wire.

Two short test samples were fabricated and deflection tested. One sample was without final outer jacket, consisting only of the sensing wire, braided dielectric, and shield braid. The other sample was complete. The sample without outer jacket was noted to be much less sensitive than that of the control sample. (The control was a sample of the same sensing wire incorporated in the braided cable and tested before shipment to Hi Temp in a precursor cable.) Inclusion of the outer jacket brought sensitivity back to normal. The jacket was found necessary to add stiffness to the transducer, ensuring that external deflection due to a "pressure" signal would not be absorbed by the braid. It is important that deflection of the medium is carried through to the sensing wire unattentuated; otherwise a loss in sensitivity will result. Figure 27 illustrates the transducer sensitivity testing. The transducer's specifications are listed in Table III.

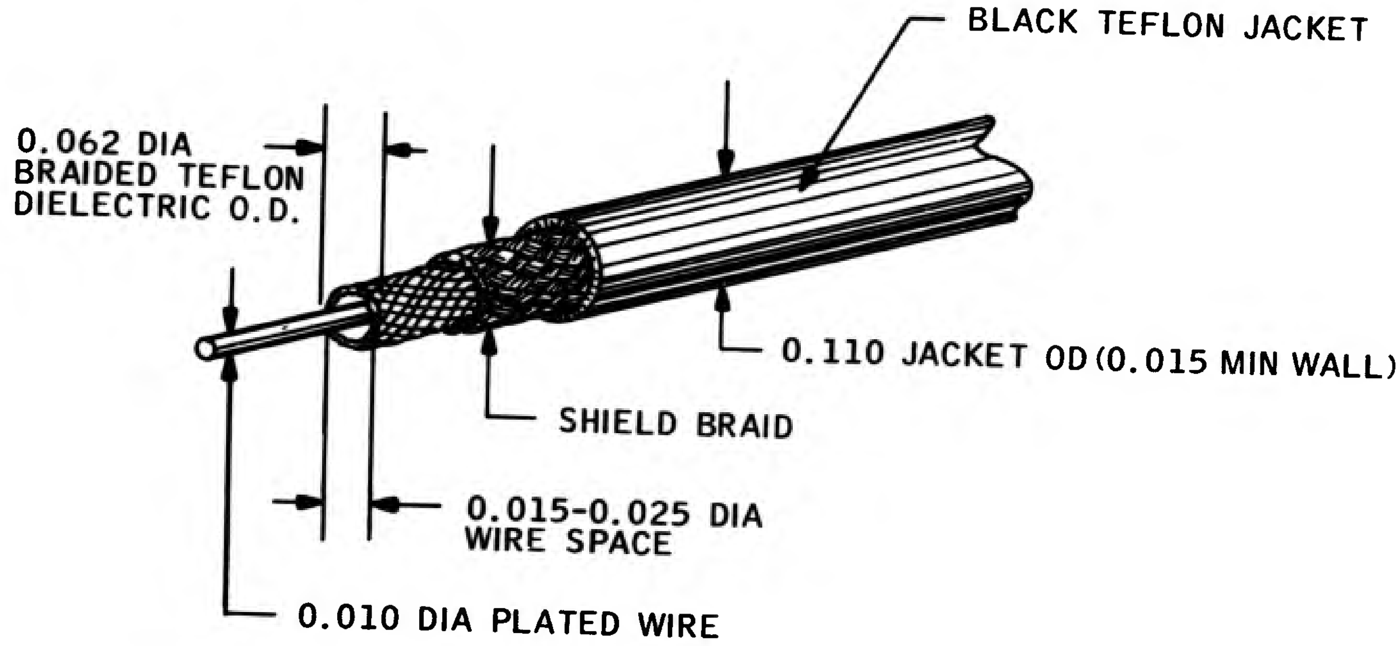
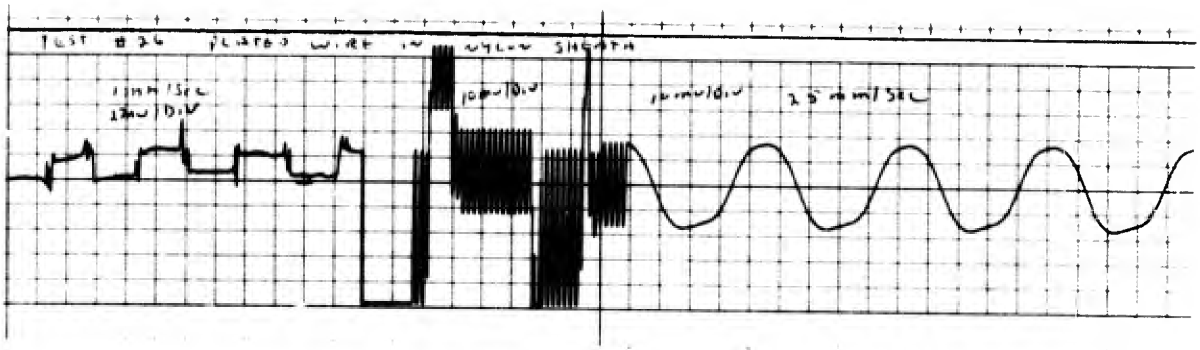
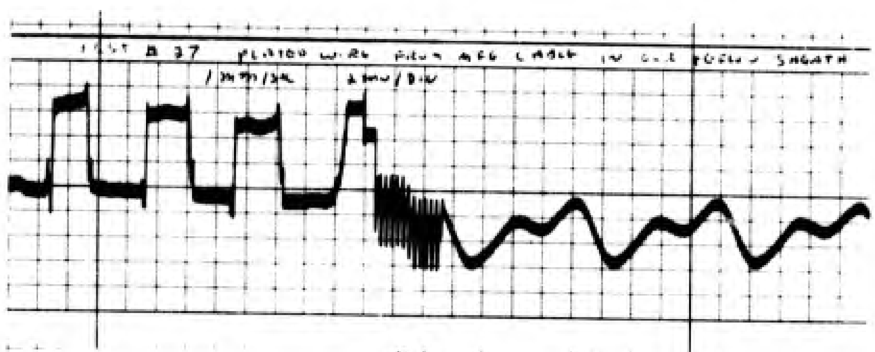


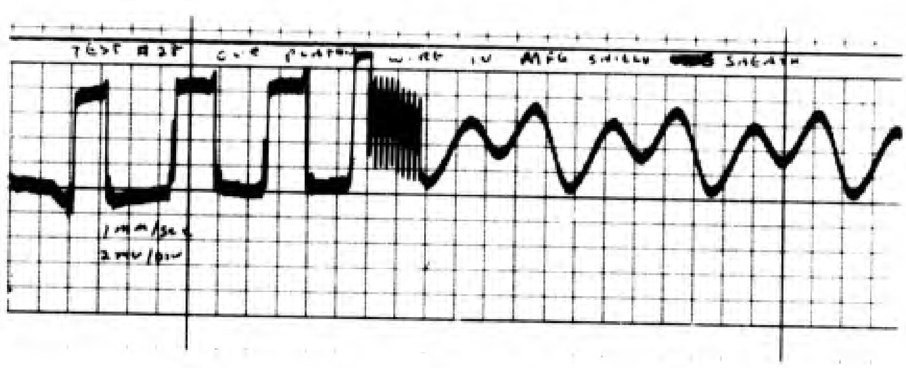
Figure 26. Transducer Cable Design



(a)



(b)



(c)

Figure 27. Transducer Sensitivity

a. Transducer without Outer Jacket
b. Braided Dielectric – Complete Transducer (Including Jacket)
c. Sensing Wire from b. in Control (Precursor) Coaxial Cable

TABLE III. TRANSDUCER SPECIFICATIONS

CONSTRUCTION

DIELECTRIC – 24 STRANDS 0.014 FEB MONOFILAMENT BRAIDED TUBE

ID - 0.020 - 0.025 INCH
OD - 0.070 - 0.080

CENTER CONDUCTOR – 0.010 INCH DIAMETER PLATED WIRE. WIRE MUST BE FREE INSIDE BRAIDED TUBE.

SHIELD BRAID – SILVER-PLATED COPPER 90 PERCENT COVERAGE.

OD 0.090 MAX.

OUTER JACKET – FEP TEFLON OD 0.120 MAX.

COLOR – BLACK

LENGTH – 330 FT. MINIMUM

FABRICATION – WIRE MUST BE FREE FROM MECHANICAL STRESS DURING FABRICATION.

Two 100-meter transducers were ordered to the specifications of Table III. The two, when received, deviated considerably from the specification. The major deviation was in the tightness of the sensing wire within the braided dielectric. While it should have been possible to move 300 feet of sensing wire through the dielectric clearance hole with less than a 2-pound total pull, it required over 2 pounds pull to move a 1-foot length of wire. A test of a short segment of the cable, however, indicated that sensitivity was adequate and that no noticeable degradation of the sensing wire had occurred during fabrication. The delivered transducers had had FEP/TFE tape wrapped around them and were heat-fuzed to the braided dielectric, ostensibly to prevent sensing wire penetration of the braid during manufacture. The stiffness of the 0.010 wire obviated any need for the tape, and it was deleted from the next transducer ordered. Improper build instructions had been issued to the cable production floor and the first transducer was inadvertently cut at the 200-foot mark.

The surviving cable was connected, continuity tested, and installed for deployment testing in the field by use of a Pipe Piper Cable Plow. No meaningful test data was obtained because it was severed in three places by animals before testing could be undertaken.

F. DRIVER/DETECTOR DEVELOPMENT

The driver/detector development effort encompassed two tasks. First, an order of magnitude signal-to-noise ratio improvement was required; second, the current drive techniques utilized in previous efforts had created a multiple loop current standing wave along the transducer length. Since transducer sensitivity is proportional to the value of current drive, sensitivity nulls were created at current nulls along the line. It was a major goal of this program to eliminate these nulls and create a uniform line.

1. Null Elimination

The first consideration for a uniform line is to select an operating frequency which will produce less than 6 db sensitivity unbalance from attenuation. For the 10-mil line, attenuation was measured to be 0.04 db/meter/MHz. Thus, for a 100-meter line, 6 db of attenuation would occur at a frequency of $f = 6/4$ MHz = 1.5 MHz. As all testing was done on an 80-meter line, f_{max} was equal to 1.5/.8 or 1.88 MHz. Maximum operating frequencies were thus constrained to around 2 MHz. (Refer to Figure 28.)

The null reduction candidates were multi-frequency drive, frequency hopping, swept frequency, and phase hopping.

All of the candidates (except phase hopping) utilized the principle of multiple drive frequencies. Each frequency develops a corresponding current standing wave pattern. With a judicious choice of frequency, current nulls can be positioned over current peaks thus averaging out the sensitivity along the line. Frequency hopping and sweeping are simply different implementations of the same concept. All of these concepts were fabricated and tested with little meaningful results. In retrospect we can see why poor performance of these concepts should be expected.

If we examine the basic standing wave pattern sensitivity equation

$$S = Kf \exp(-K_2 Xf) \sin\frac{2\pi}{\lambda} \left(\frac{r\lambda}{2} - X\right)$$

we see that sensitivity is proportional to frequency. Thus, the ideal patterns of Figure 29 result from adjusting for equal drive amplitudes of two drive frequencies. Since the best we can ever expect from this approach is a three-to-one null-to-peak ratio, the effects due to frequency must be reduced. By reducing the drive level of the higher frequency we can conceivably achieve the situation of Figure 30 in which we have a 1.3-to-one peak-to-null ratio.

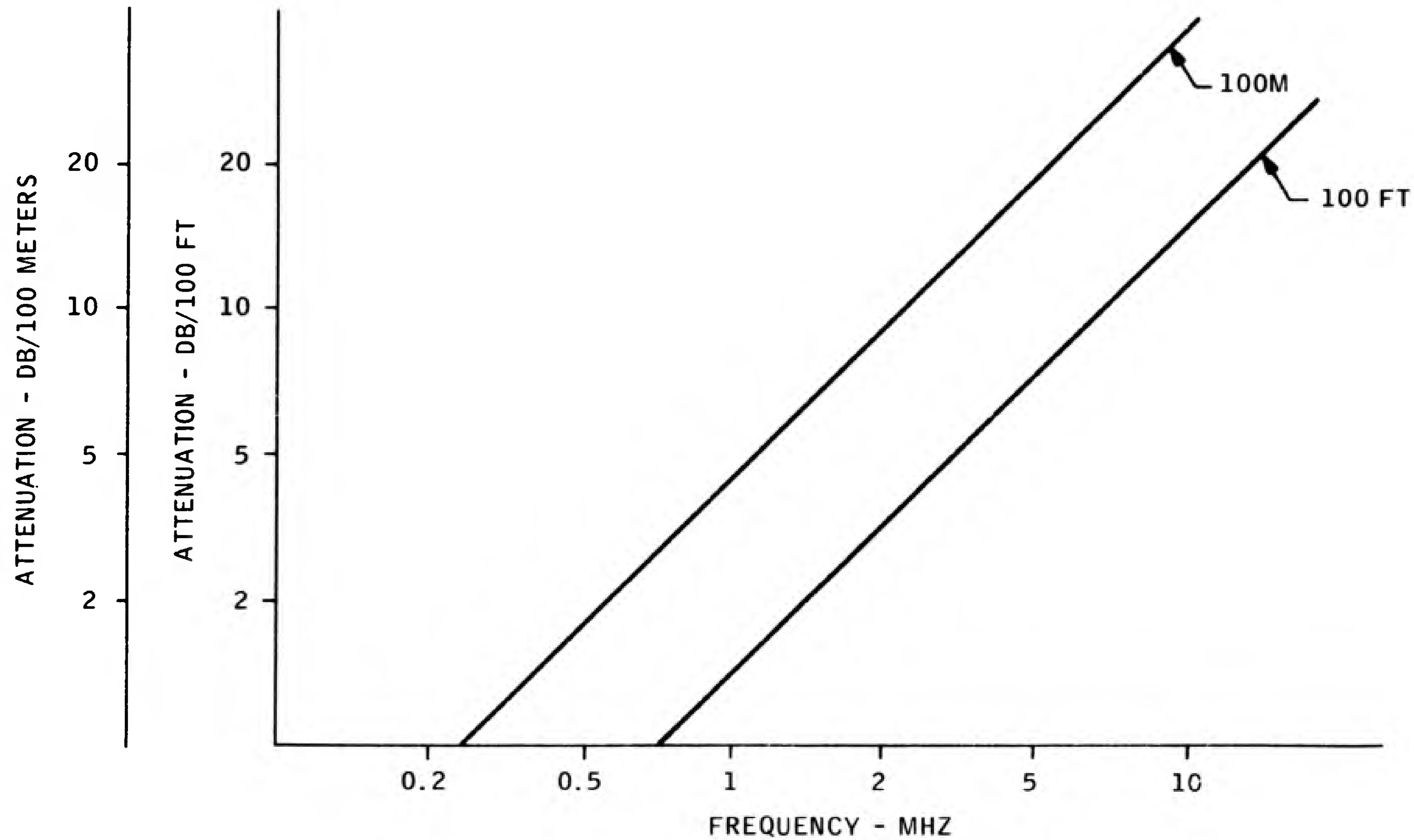


Figure 28. Total Transducer Attenuation

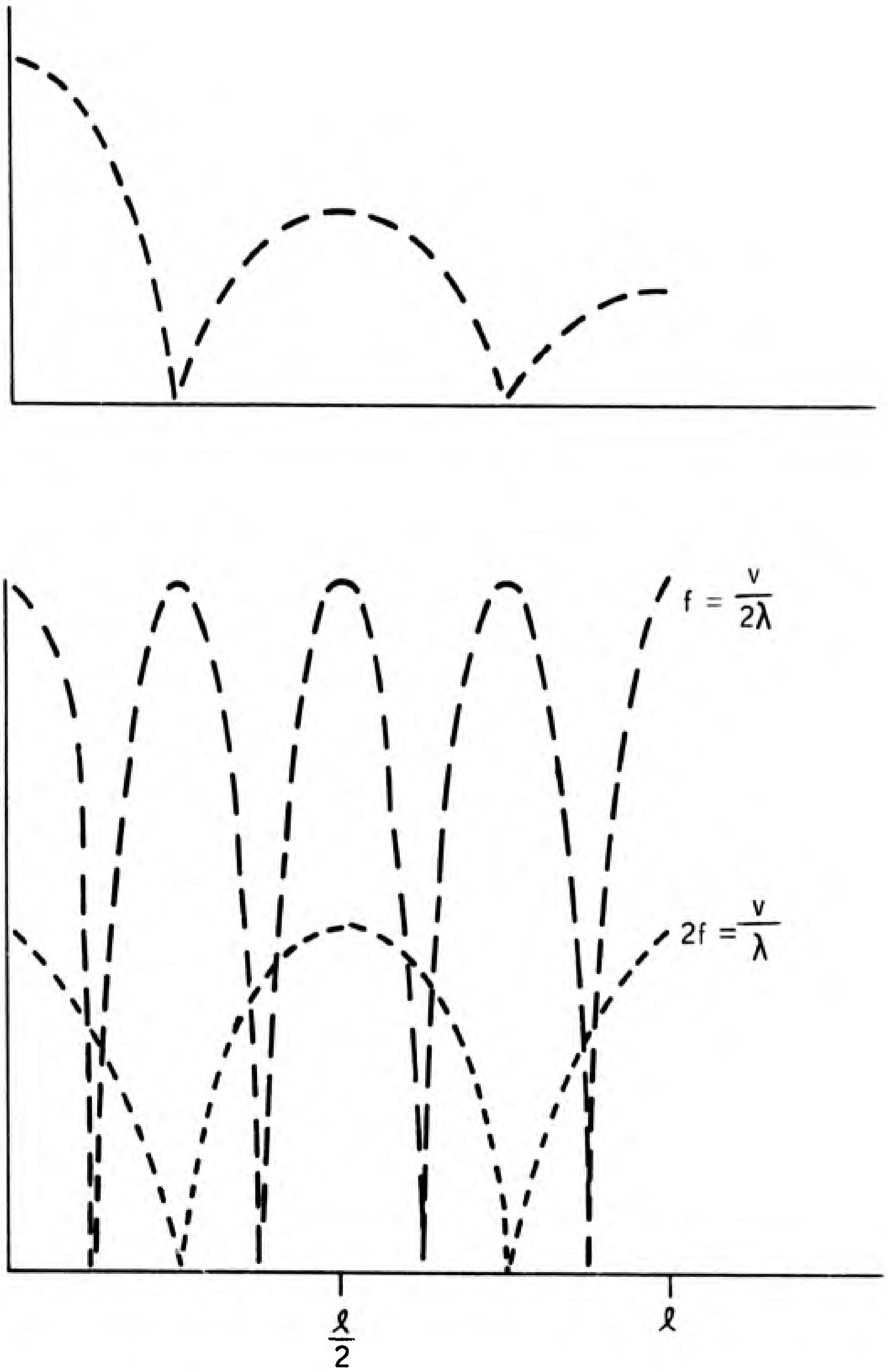


Figure 29. Ideal Standing Wave Pattern Sensitivity at λ and 2λ Drive Frequencies

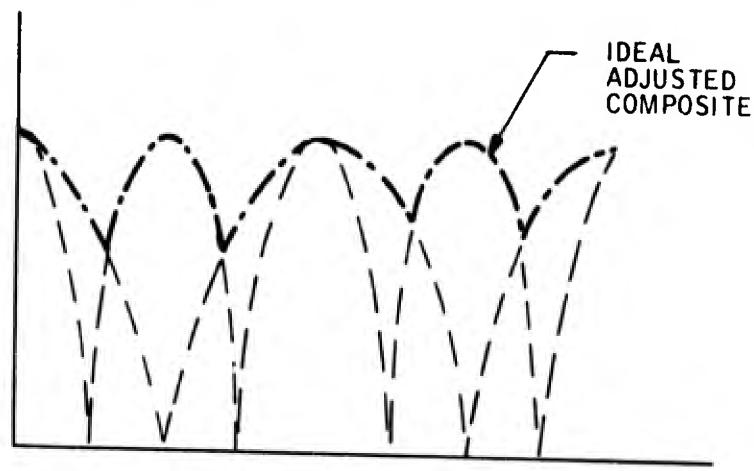


Figure 30. Ideal Standing Wave Pattern Sensitivity at λ and 2λ Drive Frequencies Adjusted for Equal Sensitivity from Each Drive Frequency.

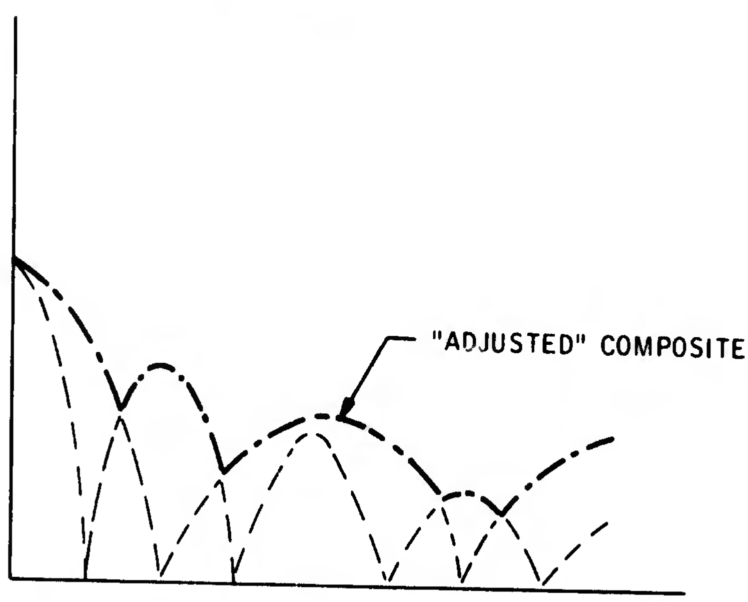


Figure 31. Standing Wave Pattern Sensitivity at λ and 2λ Adjusted for Equal Sensitivity Due to Each Drive Frequency

Unfortunately, attenuation must also be considered. The operating frequencies are high enough (to achieve the λ and a 2λ points) that the exponential attenuation term becomes significant. If we assume a 6 db attenuation for the λ frequency we automatically obtain a 12 db attentuation for the 2λ frequency. The adjusted composite (Figure 31) illustrates the most optimistic pattern obtainable with a four-to-one peak-to-null ratio. A noise ceiling will further diminish the four-to-one figure. Figure 32 illustrates the effects if drive level compensation is not utilized. If anything, the results are worse.

From an implementation standpoint it became obvious that the two frequencies could not just simply be summed onto the transducer. The envelope detector utilized would choose only the drive frequency with the highest amplitude and completely ignore the lower amplitude drive. This occurs as the higher amplitude back biases the detector. Thus, to properly utilize the multiple frequency concepts, separate filters and detectors would be required, as indicated in Figure 33. The complexity of the projected system was dismaying in its extent and opened the door to any other viable solution.

The phase hopping concept produced the most viable concept of all the null reduction techniques. Its utility, however, was reduced by physical realities as we shall see. Preliminary testing of the phase hopper was conducted with the 16-foot transducer. Figure 34 illustrates the patterns that result from this line being driven at its quarter wavelength resonant point and the same line driven at the same frequency, only with the current phase shifted relative to the voltage. The actual patterns are shown in Figure 35 and indicate the actual data from a 16-foot transducer. The phase hopper utilized a multi-vibrator-to-switch PIN diodes in and out of the circuit. The PIN diodes provide a very low RF impedance ($\approx$ 1 for 10 ma forward current) when biased on and a very high RF impedance when back-biased. The alternately switch two values of capacitance across the transducer, thereby adjusting the phase of the current with respect to the voltage. Drive frequency is the same for either phase. The phase hopping driver schematic is illustrated in Figure 36.

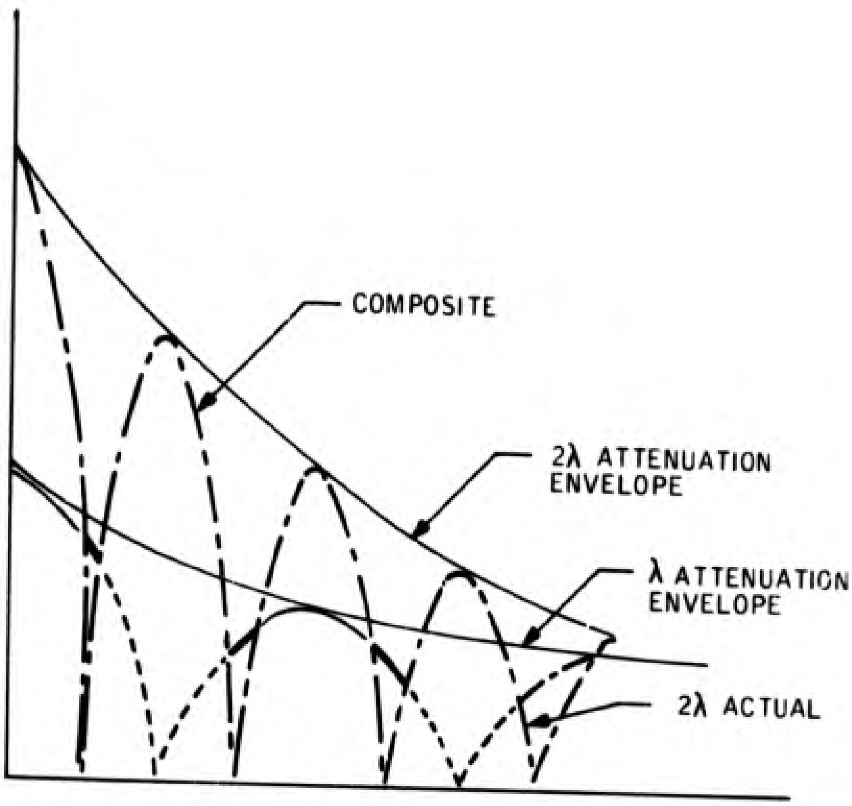


Figure 32. Standing Wave Pattern Sensitivity at λ and 2λ Including Attenuation Effects

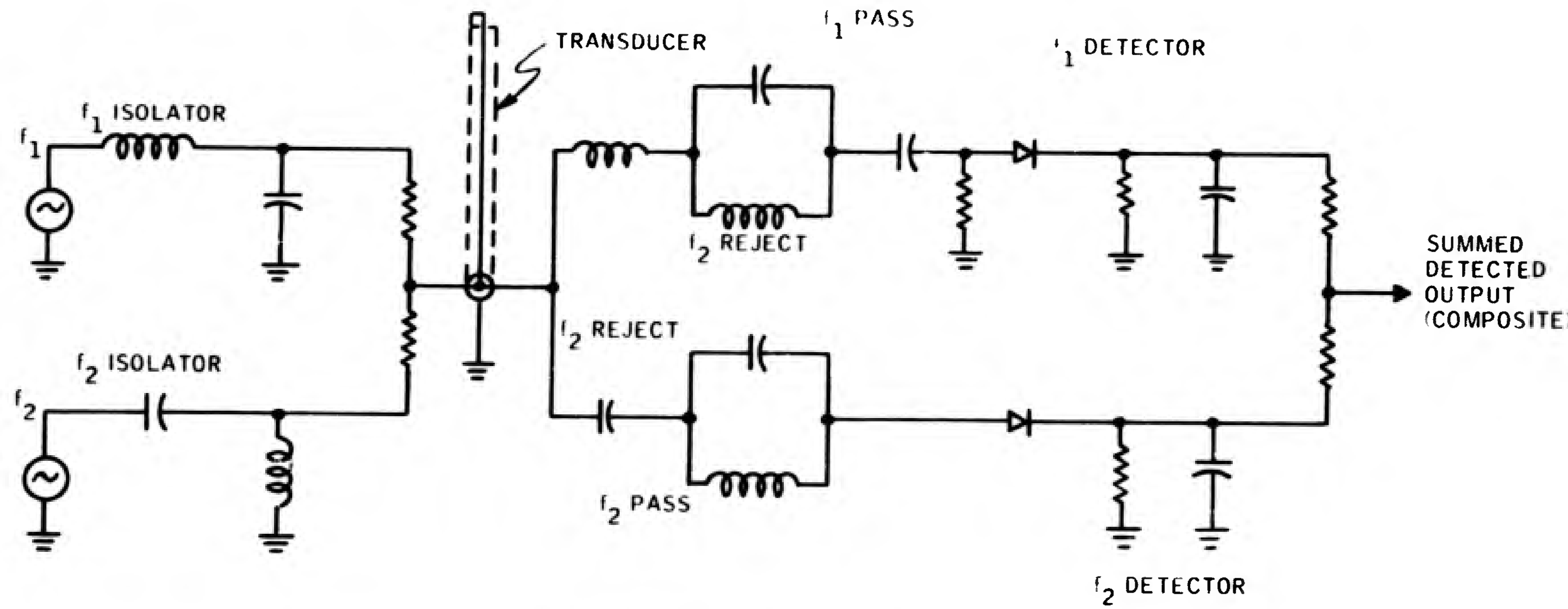


Figure 33. Two-Drive Frequency Concept Isolators

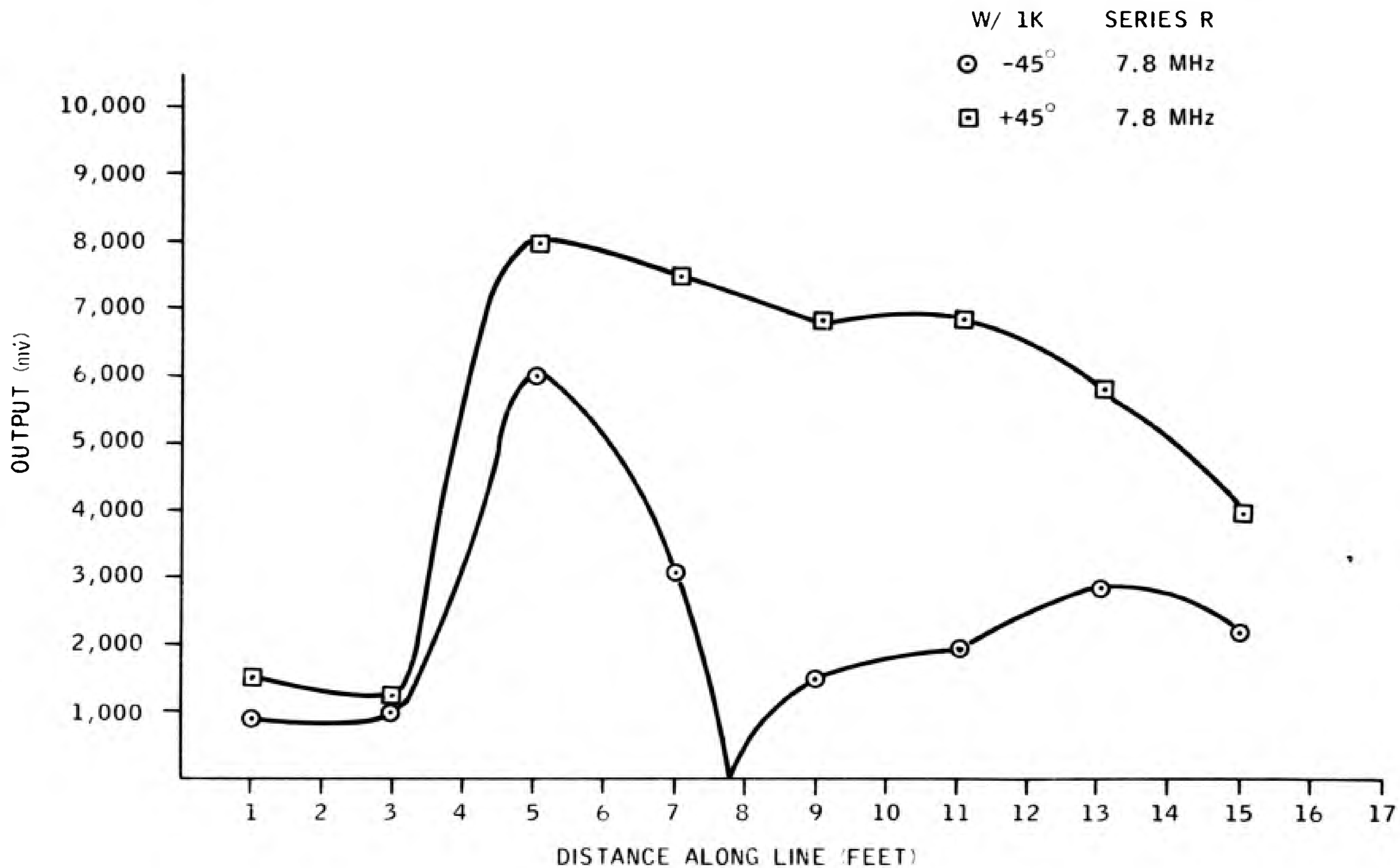


Figure 34. Sixteen-Foot Line Sensitivity at Two Phase Settings (Phase Measured by Victor Impedance Meter and Adjusted with a Variable Shunt Capacitor)

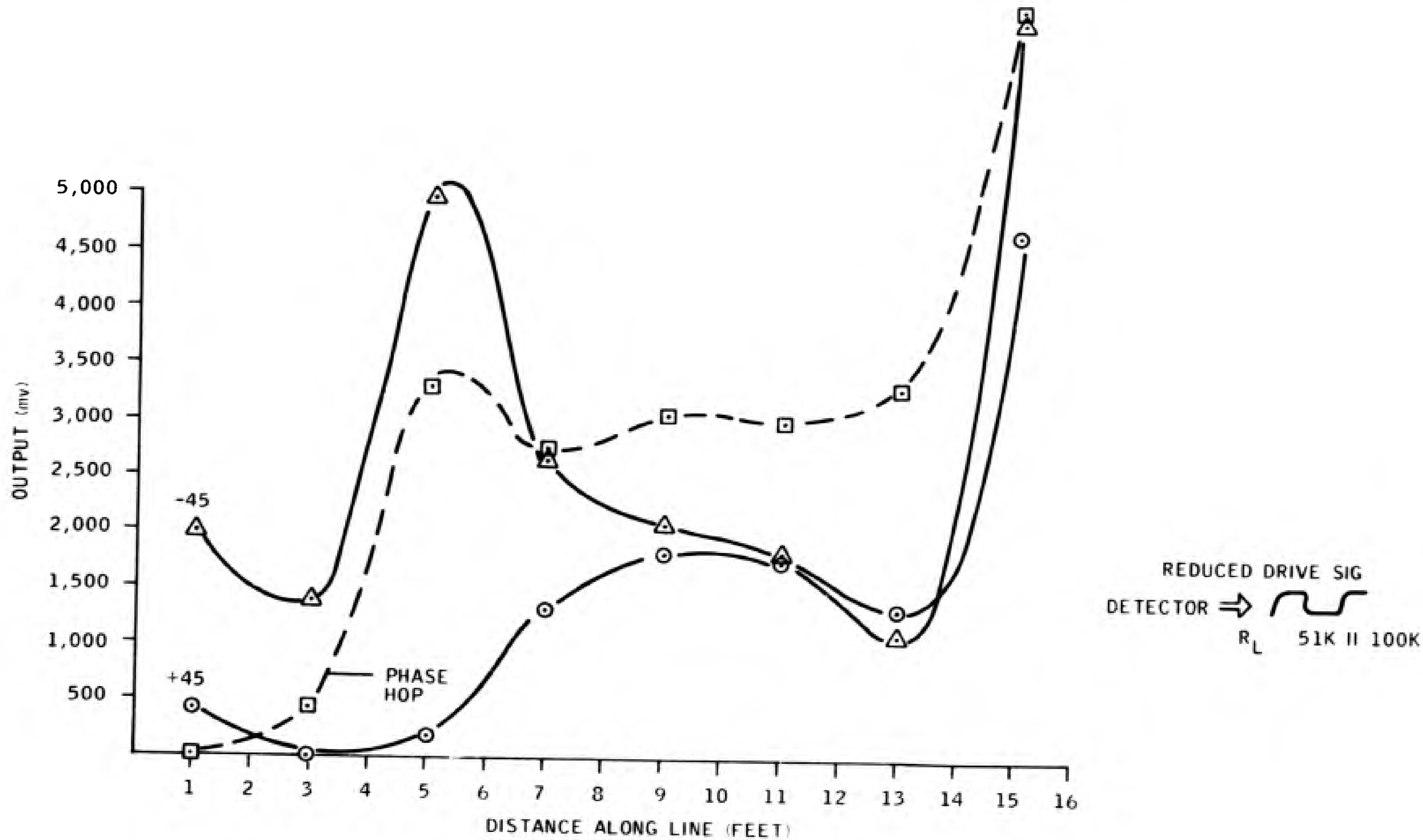


Figure 35. Phase Hopping Driver Sensitivity - 16-Foot Line
Note: First 5 Feet of Line Is Not Functional

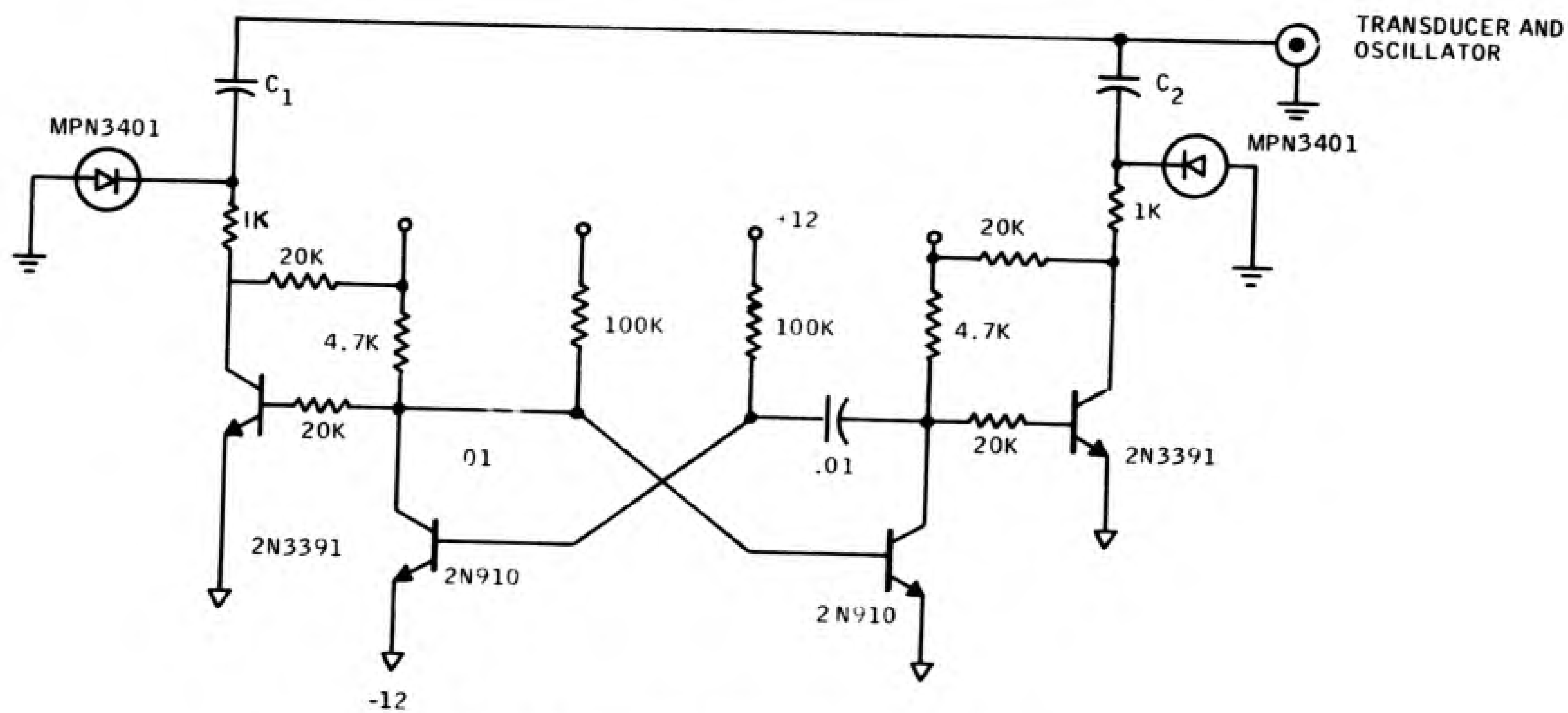


Figure 36. Phase Hopping Driver Schematic

The major problem with the phase hopper is, again, attenuation. Attenuation tends to smear the phase relationships along the line, producing variable peak-to-null performance. Utility of the phase hopper is thus limited to the frequencies near $\lambda/4$ and $\lambda/2$ where attenuation is minimal.

2. Phase Shifted $\lambda/4$ Drive

If the pattern for a $\lambda/4$ transducer is examined, it is easily seen that phase shifting the current waveform results in the pattern of Figure 37. For this pattern the peak-to-null ratio is 1.4-to-one, less than 3 db change over the length of the transducer; also, attenuation at $\lambda/4$ is negligible, less than 1 db. This approach was used in the final transducer design and is discussed in detail in Section V-B.

The tradeoff, here, is in sensitivity. The $\lambda/4$ frequency for a 100-meter line is on the order of 200 to 300 KHz. Thus, the key to the entire effort was in achieving a very low noise driver/amplifier combination.

The low noise amplifier was achieved by using a low noise PNP differential pair preamplifier ahead of the first operational amplifier and by reducing source impedance to 5K ohms. The total amplifier is thus noise-limited by either device noise or by source resistance thermal noise. Total noise was reduced to 350 nanovolts p-p equivalent input noise (theoretical noise level was 320 nanovolts peak-to-peak).

Driver noise was reduced dramatically by removing the buffer transistors and by performing the buffer/impedance translation function with a transformer. At the same time, the oscillator FET was constrained to operate voltage-limited (using the supply for a reference) rather than current-limited (the current-limited oscillator is more subject to cycle-to-cycle fluctuation). Driver noise was thus reduced to less than equal to amplifier noise. Total system noise was reduced to 400 nanovolts peak-to-peak.

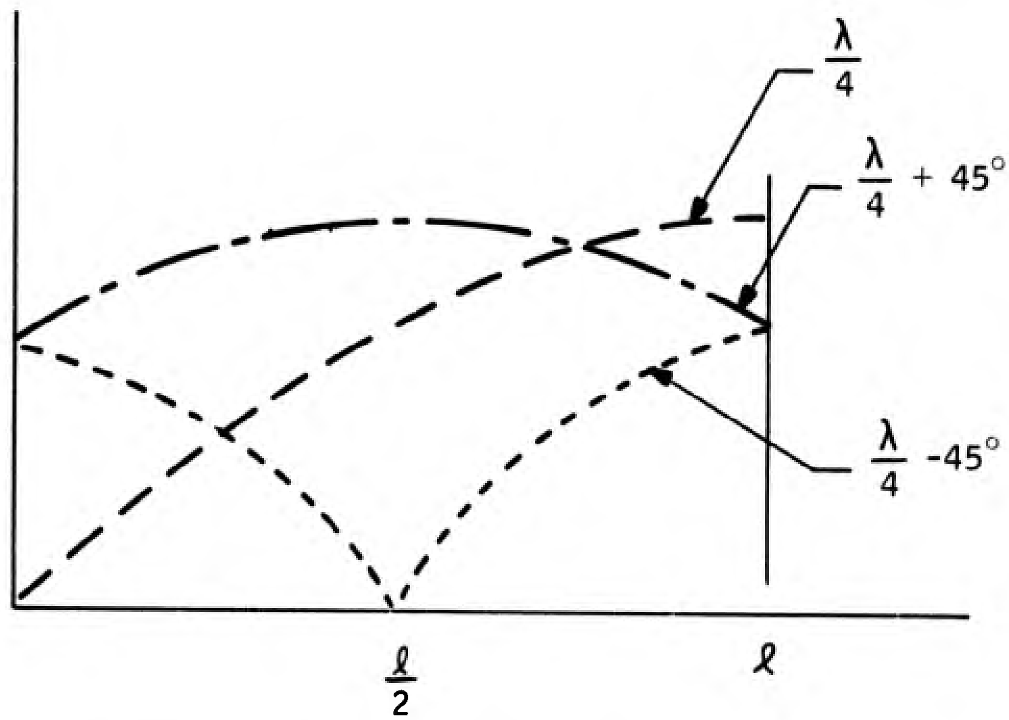


Figure 37. Results of Phase Shift on λ/4 Sensitivity

There was one incident where system noise shot up to 70 microvolts peak-to-peak. It was discovered that the toroid core used for the driver transformer was: (1) acting as a magnetometer of $2nv/\varphi$ sensitivity, and (2) was responsible for extremely large noise variation, depending on its state of magnetization. Adoption of a slug-tuned, bifilar-wound transformer eliminated this problem.

System performance in the laboratory and in the field is illustrated in Figures 38 and 39. The laboratory data was obtained with the fringing field of a solenoid driving the line at 1 Hz over the line length. No attempt at correlation of the magnetic and deflection sensitivity of the transducer was made, but prior testing established that the sensitivity ratio between the two influences was constant over the line length. The magnetic test was the more repeatable test and was often utilized during the program.

3. Logic

The program plan for the system was to collect signatures from a cable-plow-installed 100-meter transducer. The signatures were to include human, animal, and vehicle instrusions in addition to helicopter, explosion, rain and wind nuisance influences.

Rodent damage of the installed 100-meter transducer required switching data and signature collection to the 80-meter transducer installed earlier. The 80-meter line was of precursor construction where 80 meters of 10-mil plated wire was pulled into a 15-mil hole. A 10-mil copper conductor was built into the cable to act as a precursor for the plated wire. The plated wire is joined to the precursor and is pulled into the cable as the precursor is pulled out. The 80-meter transducer thus fabricated was installed in a 10 ± 2 inch deep by 4-inch-wide machine dug trench as backup to the cable-plow-installed 100-meter transducer. The 80-meter line was also attacked by rodents, but the break was found and repairs made.

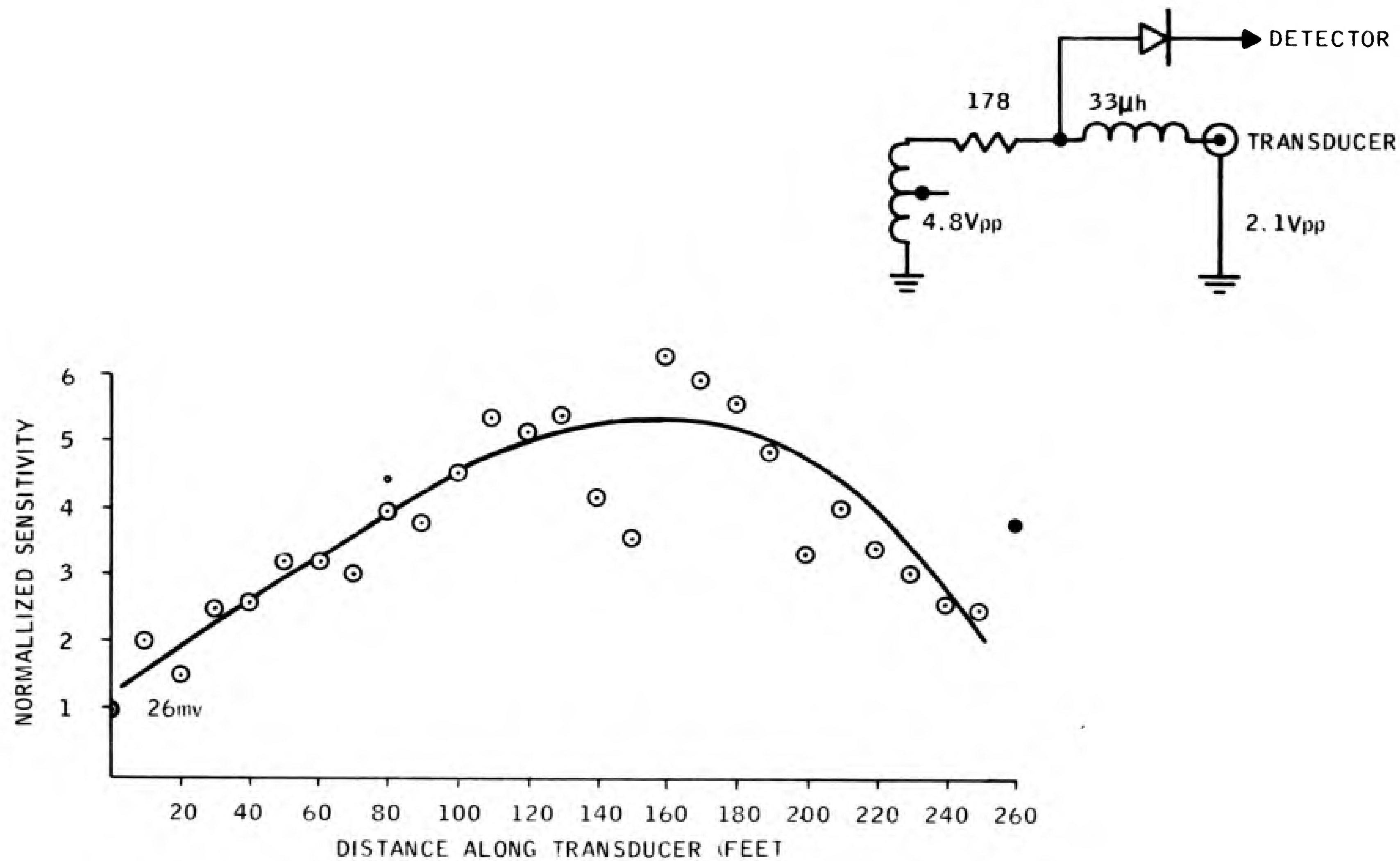


Figure 38. Transducer Sensitivity Versus Distance

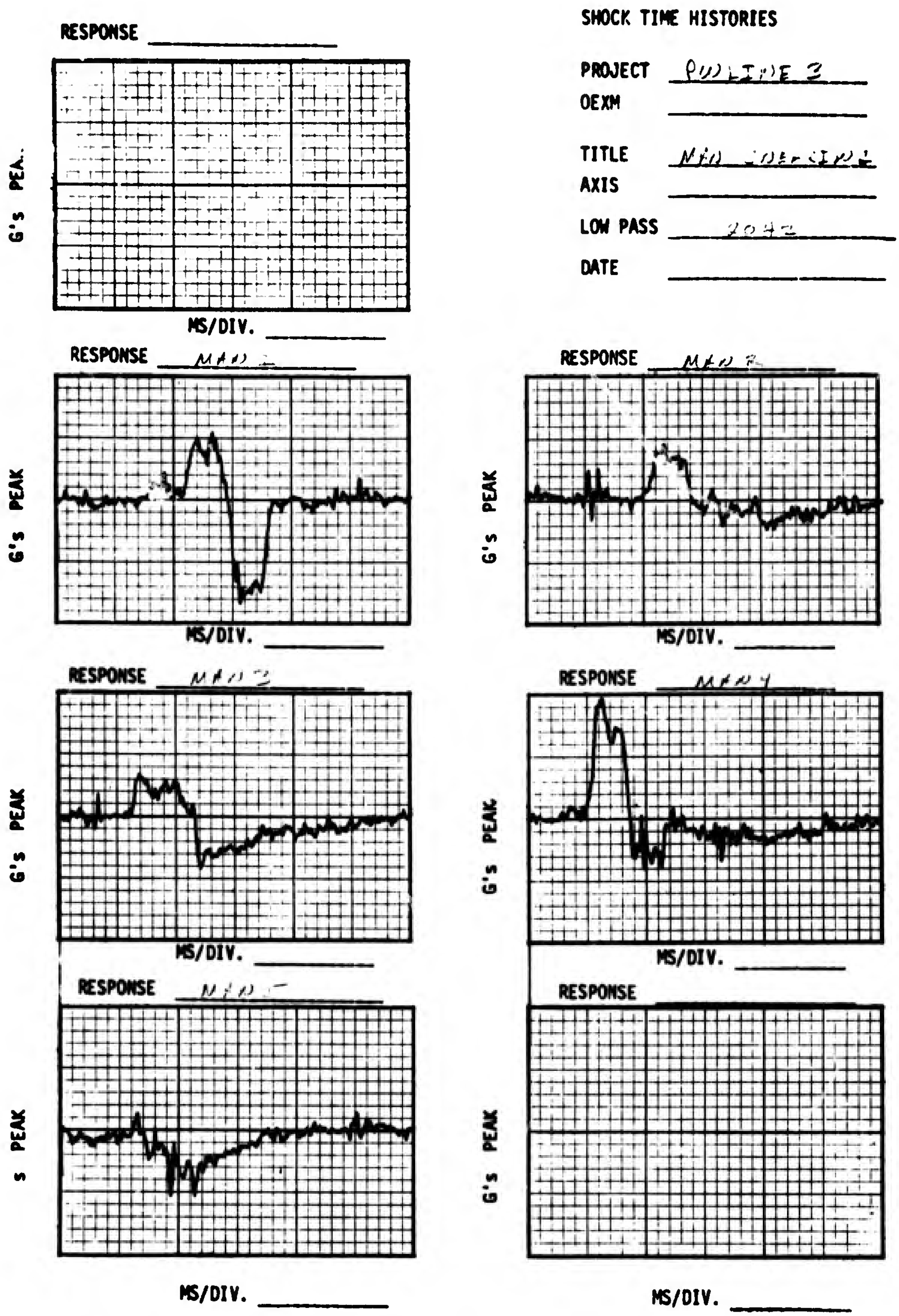


Figure 39. First HOPG Data from 260 Feet (80-Meter Line)

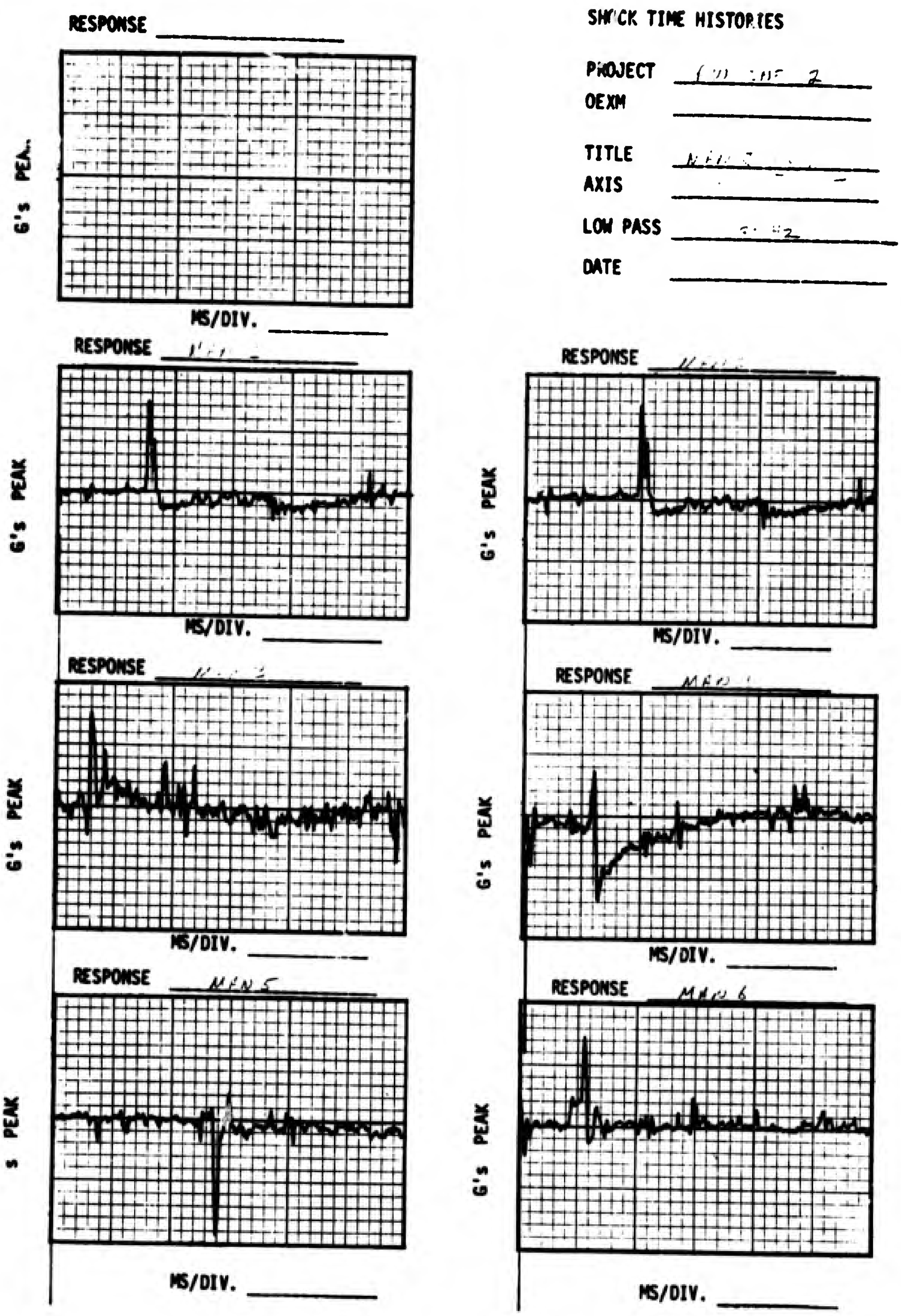


Figure 39. First HOPG Data from 260 Feet (80-Meter Line) (Continued)

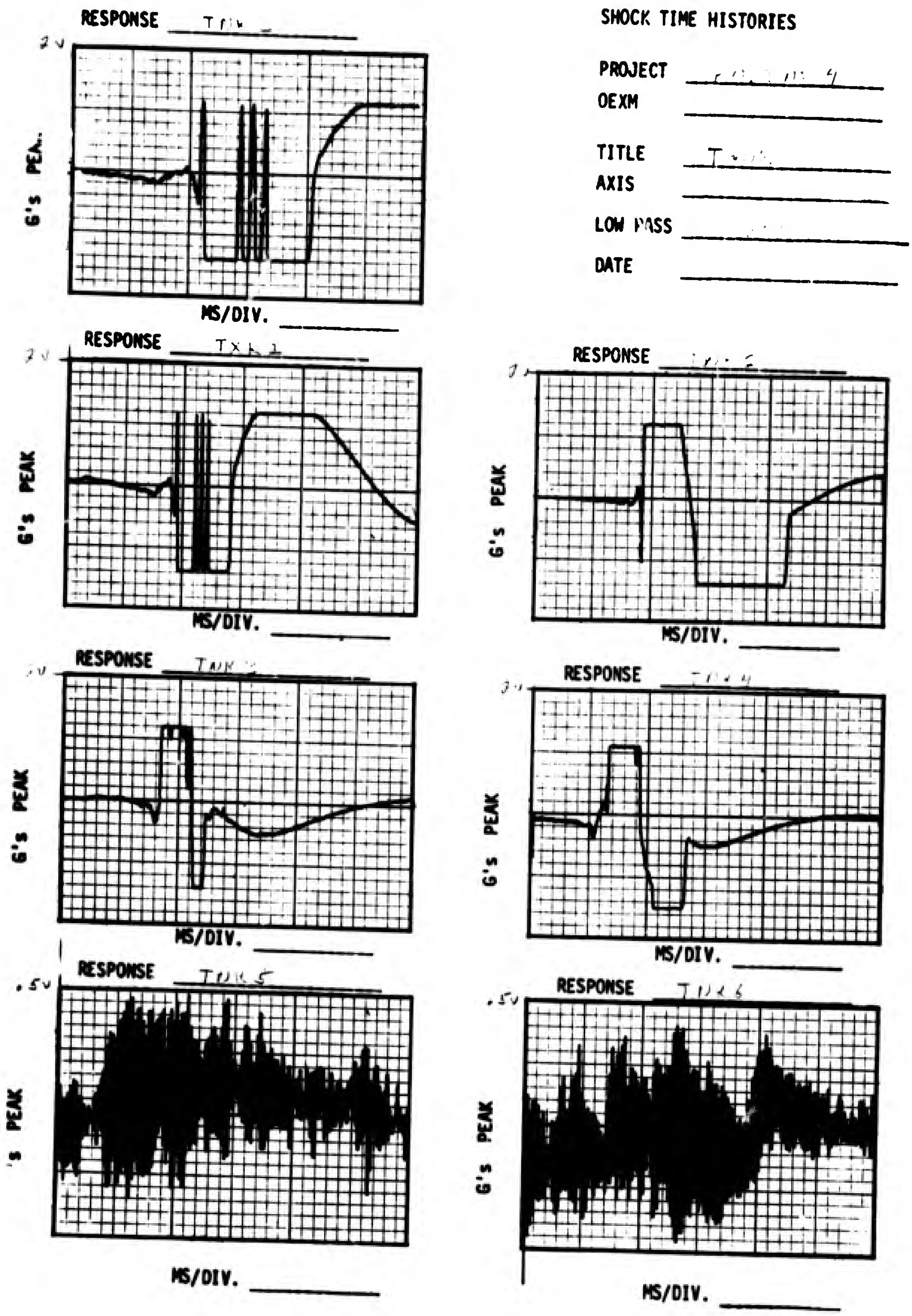


Figure 39. First HOPG Data from 260 Feet (80-Meter Line) (Continued)

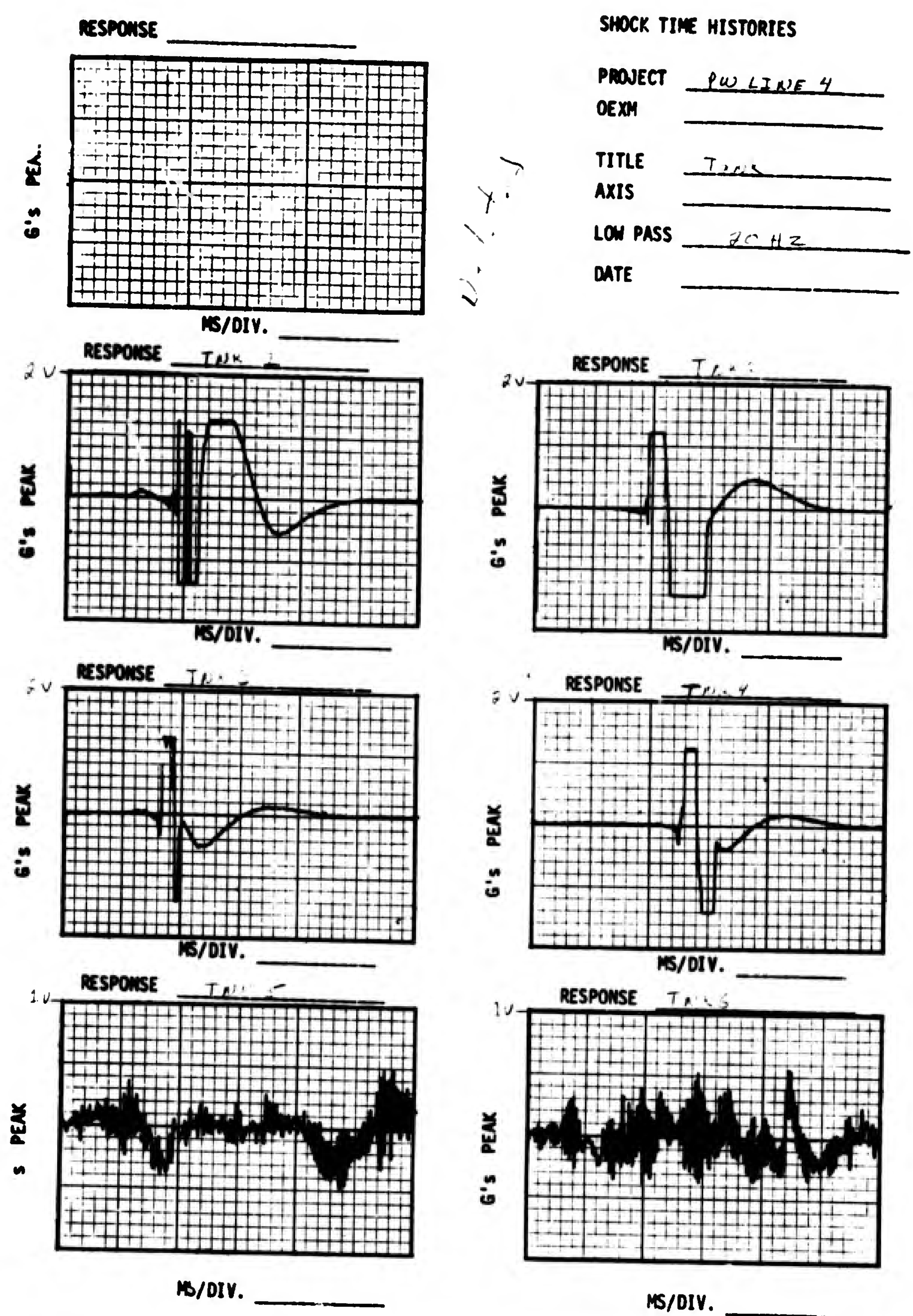


Figure 39. First HOPG Data from 260 Feet (80-Meter Line) (Continued)

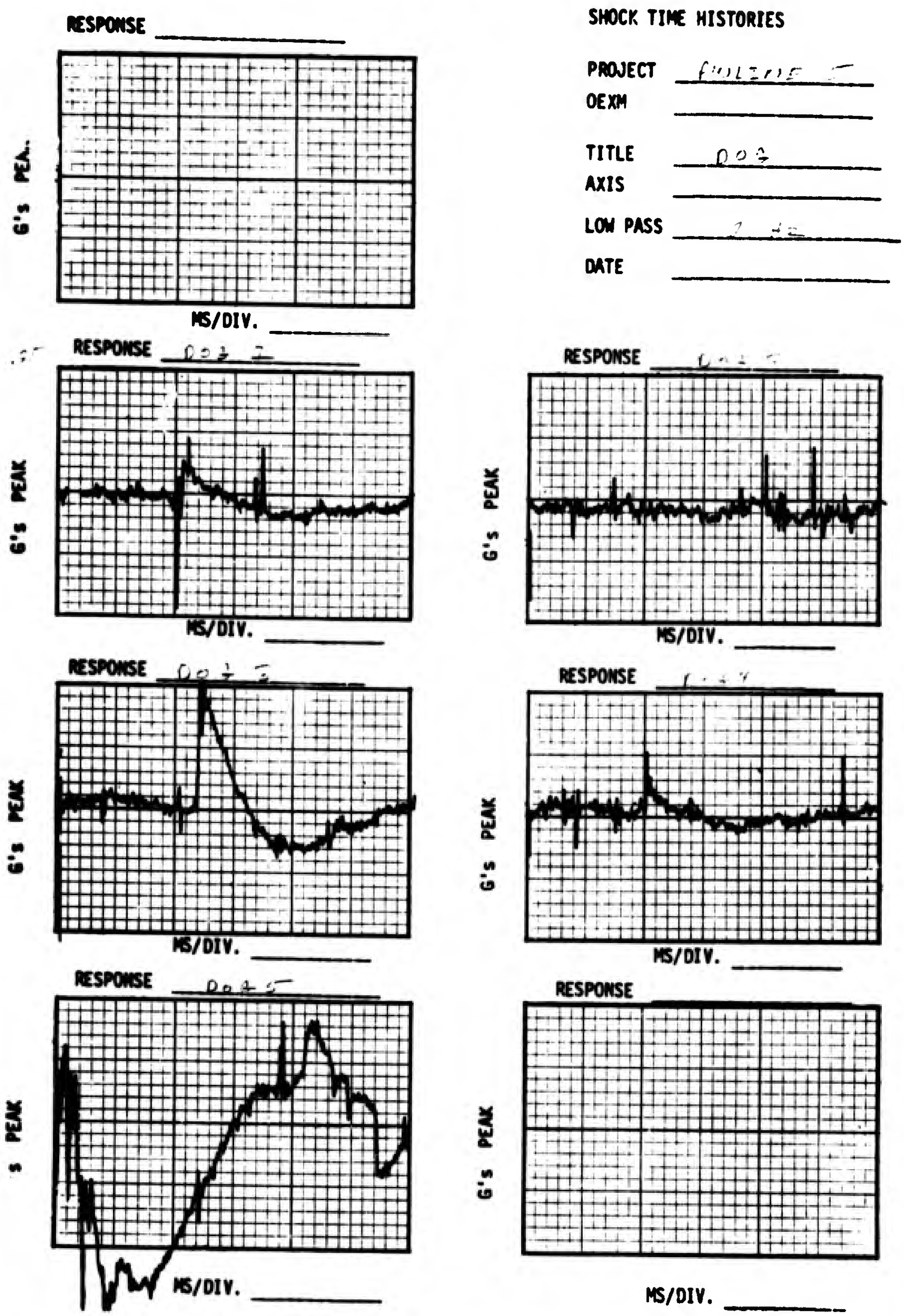


Figure 39. First HOPG Data from 260 Feet (80-Meter Line) (Continued)

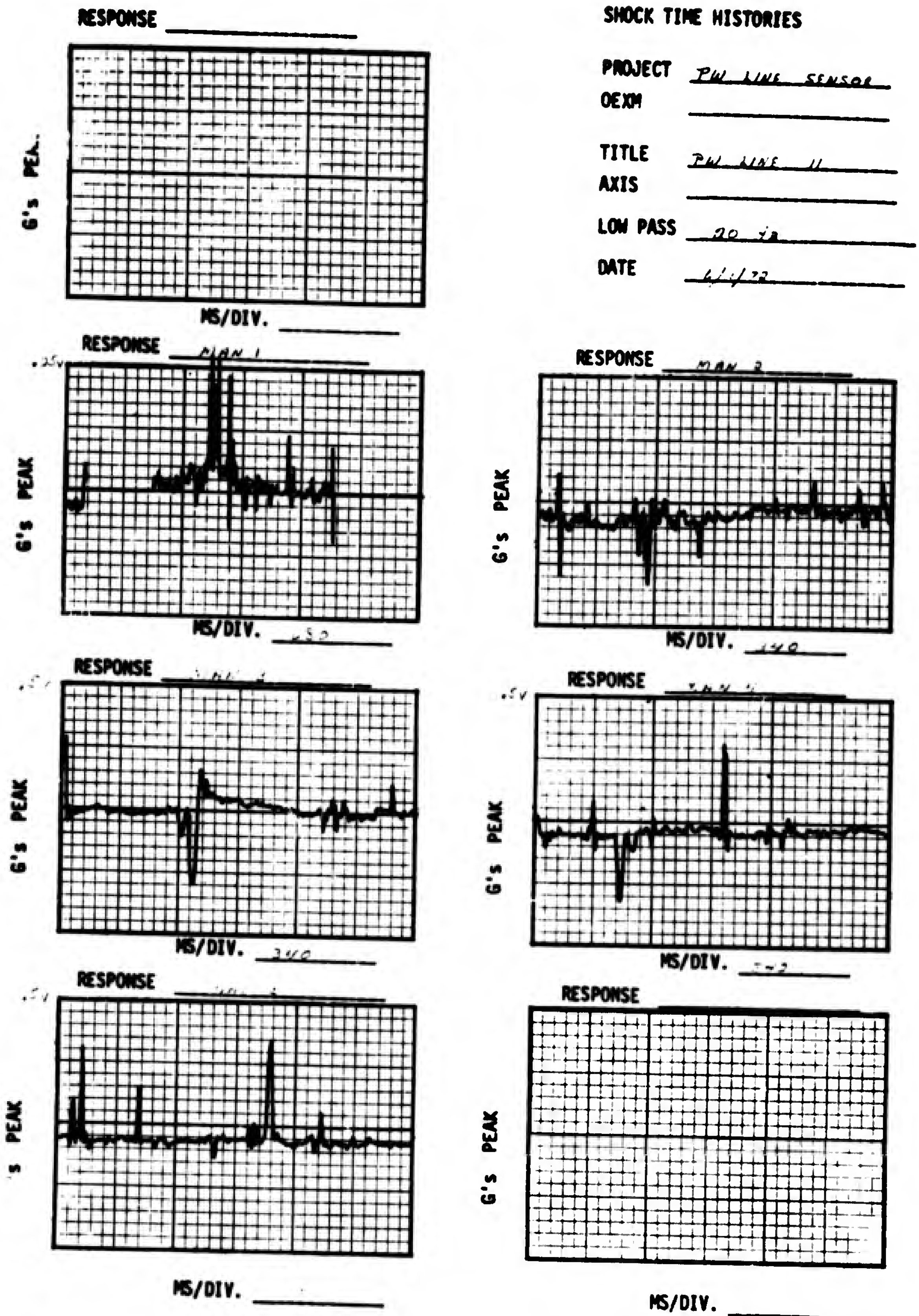


Figure 39. First HOPG Data from 260 Feet (80-Meter Line) (Continued)

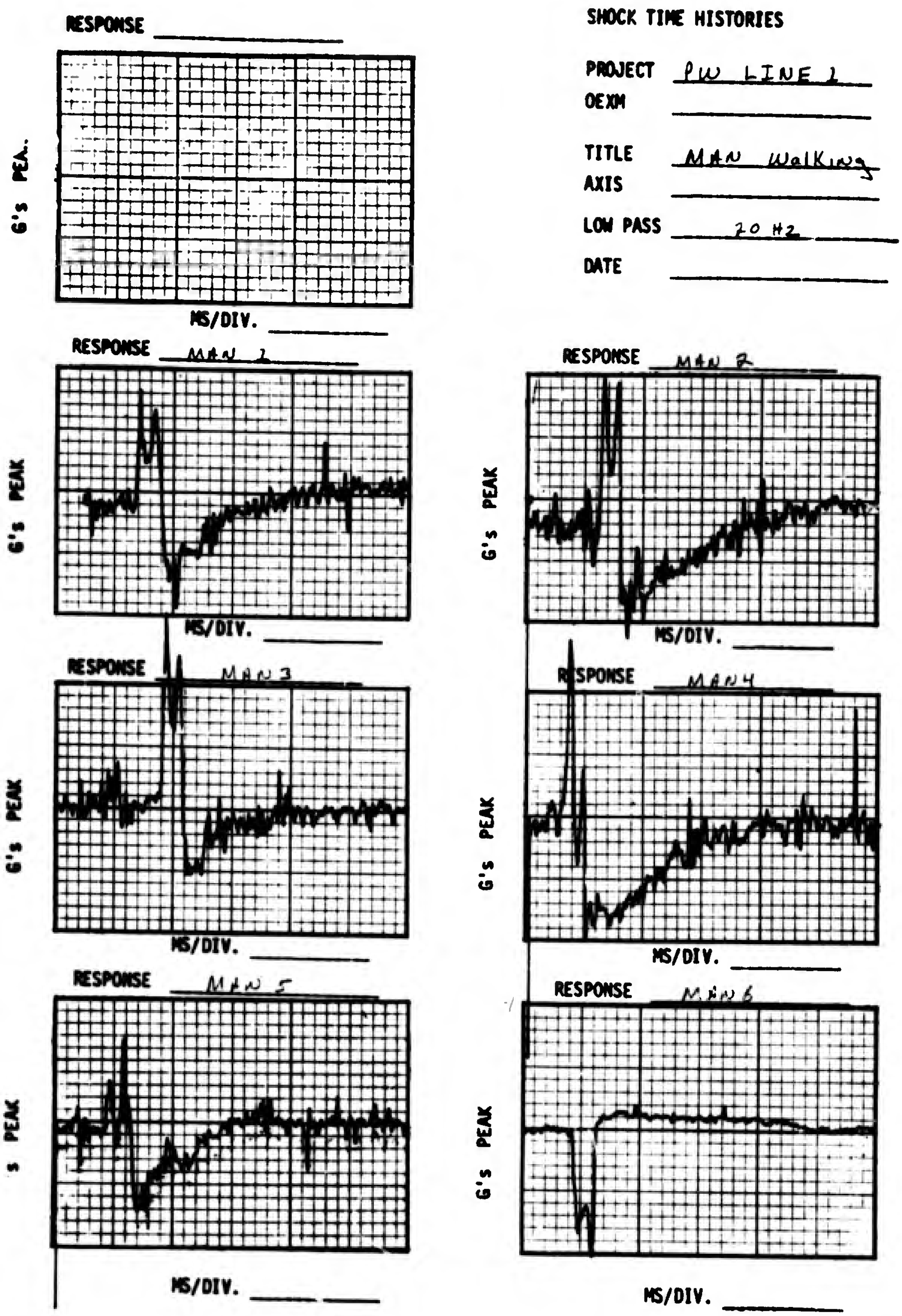


Figure 39. First HOPG Data from 260 Feet (80-Meter Line) (Continued)

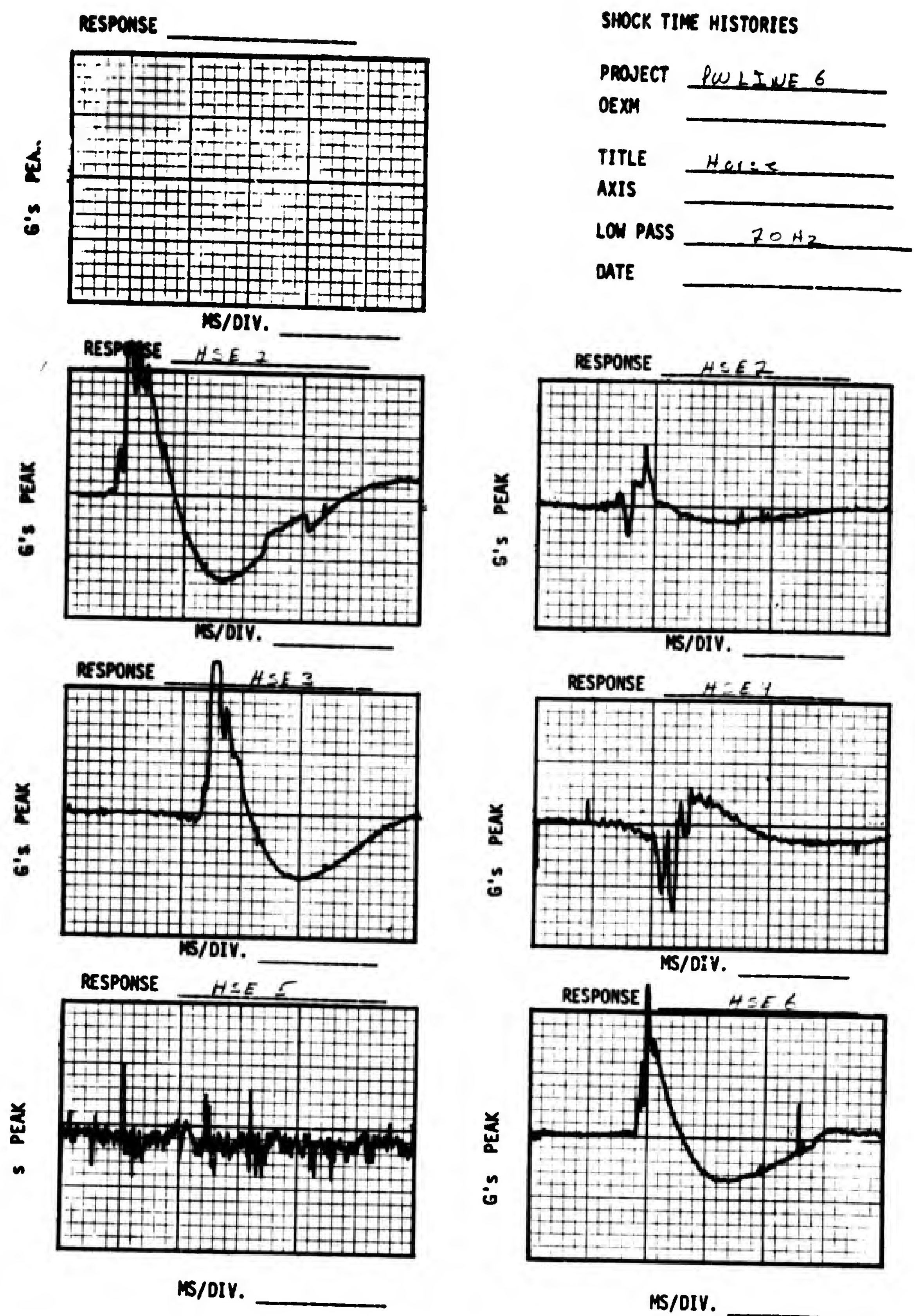


Figure 39. First HOPG Data from 260 Feet (80-Meter Line) (Concluded)

The only data obtained from the 100-meter transducer illustrated the need for proper installation tools. The blade and needle in the Pipe Piper were slightly oversized for the 0. 115-inch transducer cable and left an open slit in the ground. The open slit prevented significant earth coupling to the transducer and hence very little output. Closing the slit by driving over it with an automobile markedly improved transducer output. This problem would be alleviated by a smaller blade/needle combination, increasing the cable diameter, or by providing tamping wheels on the trailing end of the plow.

4. Amplifier Response

Amplifier frequency response is set on the lower end by the lowest anticipated intrusion velocity together with transducer detection zone. If we assume a detection zone of 3 feet on each side of the transducer and an intruder minimum velocity of 1 foot per second, the intruder will be in view for 6 seconds. This corresponds to a frequency of 0. 16 Hz. For the upper frequency limit, consider an intruder running at 30 ft. /sec. (100-yard dash in 10 sec.). Using the same parameters as above, he will be in view for 6 ft. /30 fps = 0. 2 sec. corresponding to a frequency of 5 Hz.

5. Discrimination Technique

The signatures gathered from the 80-meter transducer were digitized signature by signature suitable for computer analysis. Cursory analysis indicated that threshold-time logic would be unsatisfactory. The fairly poor signal-to-noise ratio, the high amplitude animal signatures and the potential highly variable media factors from emplacement to emplacement would make discrimination based on threshold exceedingly difficult. The only feature not greatly subject to amplitude variation is zero crossings. Accordingly, the signatures were analyzed on a zero crossing basis.

A CDC 6600 computer was programmed to extract the positive and negative zero crossings about a very small threshold in a given period. This feature was then examined for all of the signatures collected. It was noted that all human intrusions gave a period of time that was free of zero crossings. Animal signatures tended to illustrate two or more zero crossings. Normal amplifier noise gives rise to five to six zero crossings per period (after removal of the lower frequency components with a high pass tracking filter). Tracked vehicles were seen to deliver very large amplitudes and very large zero crossing rates. Wheeled vehicles crossing the transducer produce a marked lack of zero crossings for several periods (due to the very high amplitude of the signal).

A logic scheme based on the computer results was implemented with CMOS gates. The block diagram of this implementation, along with the schematic, are illustrated in Figures 40 and 41.

The logic scheme was tested with the taped signatures (nondigitized) collected from the 260-foot line. After the clock period was optimized to 1.8 sec., the logic demonstrated good detection performance.

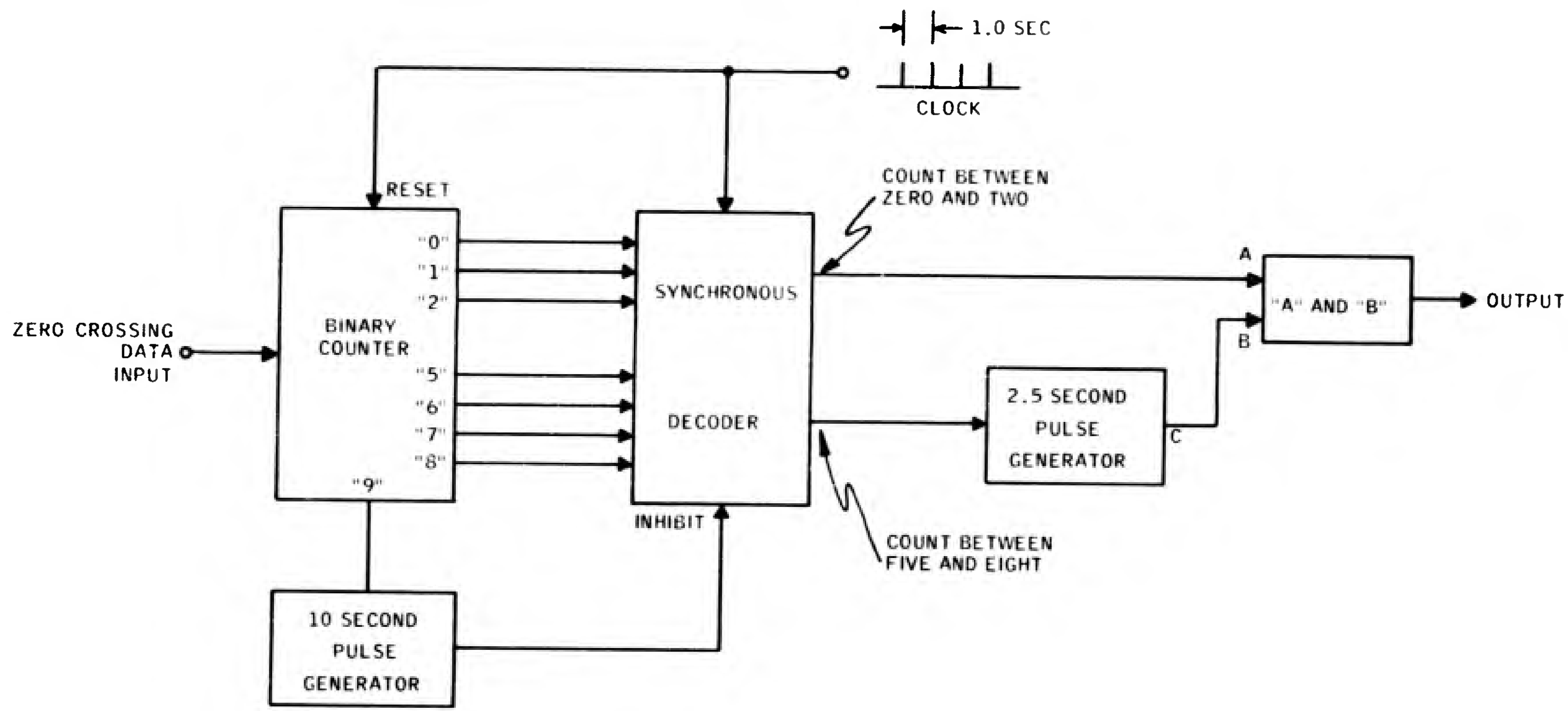


Figure 40. Zero Crossing Logic Block Diagram

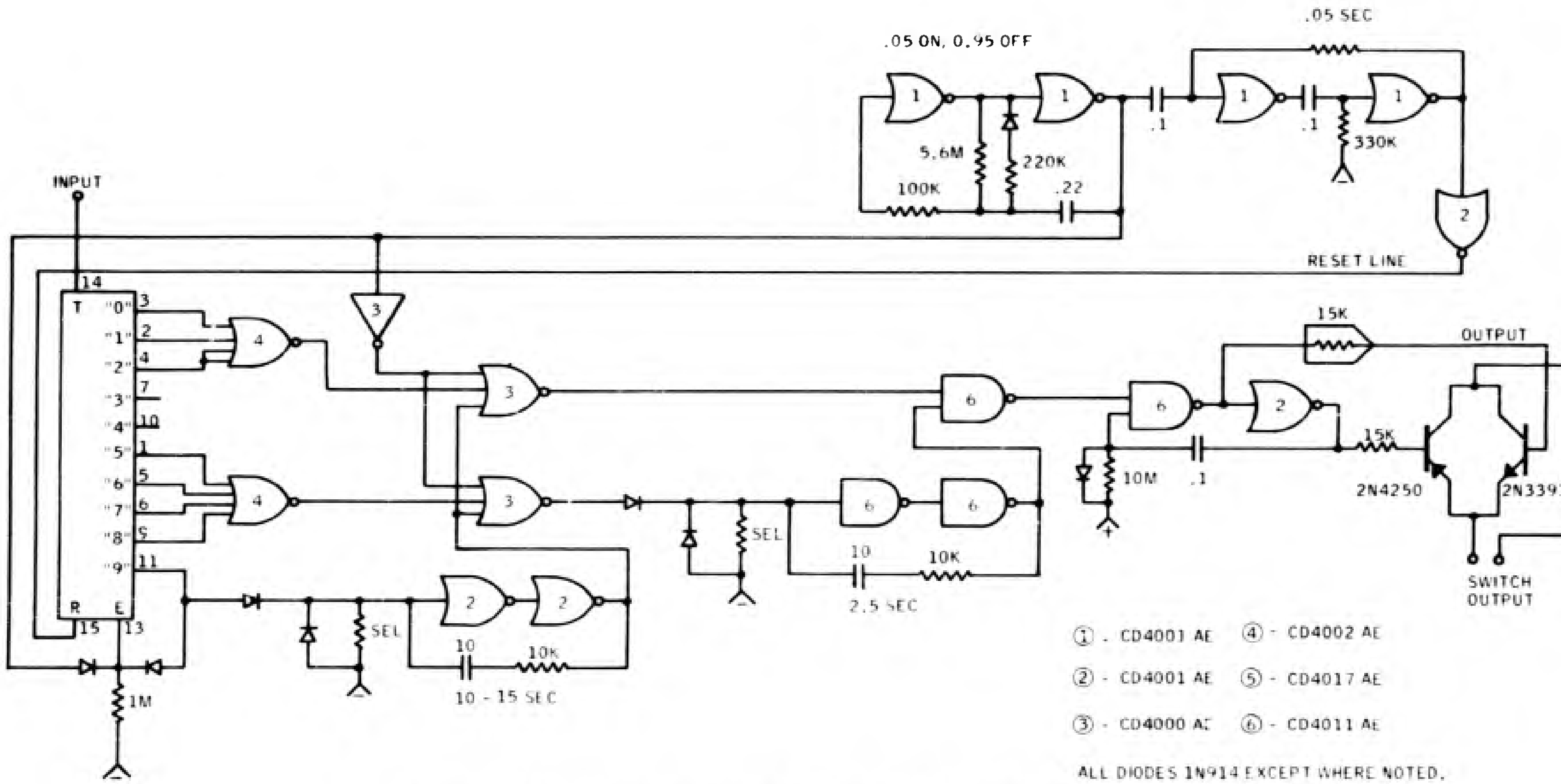
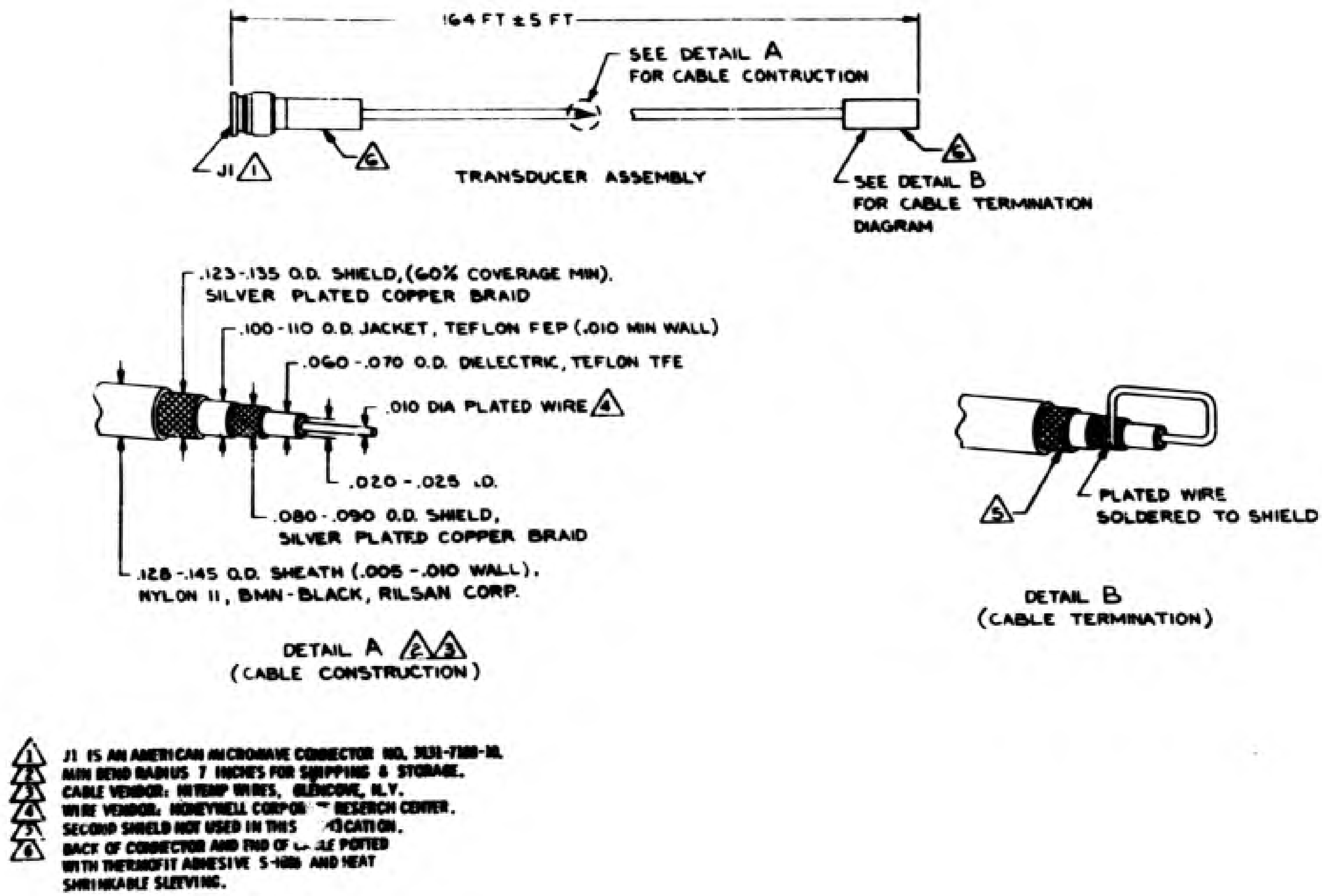


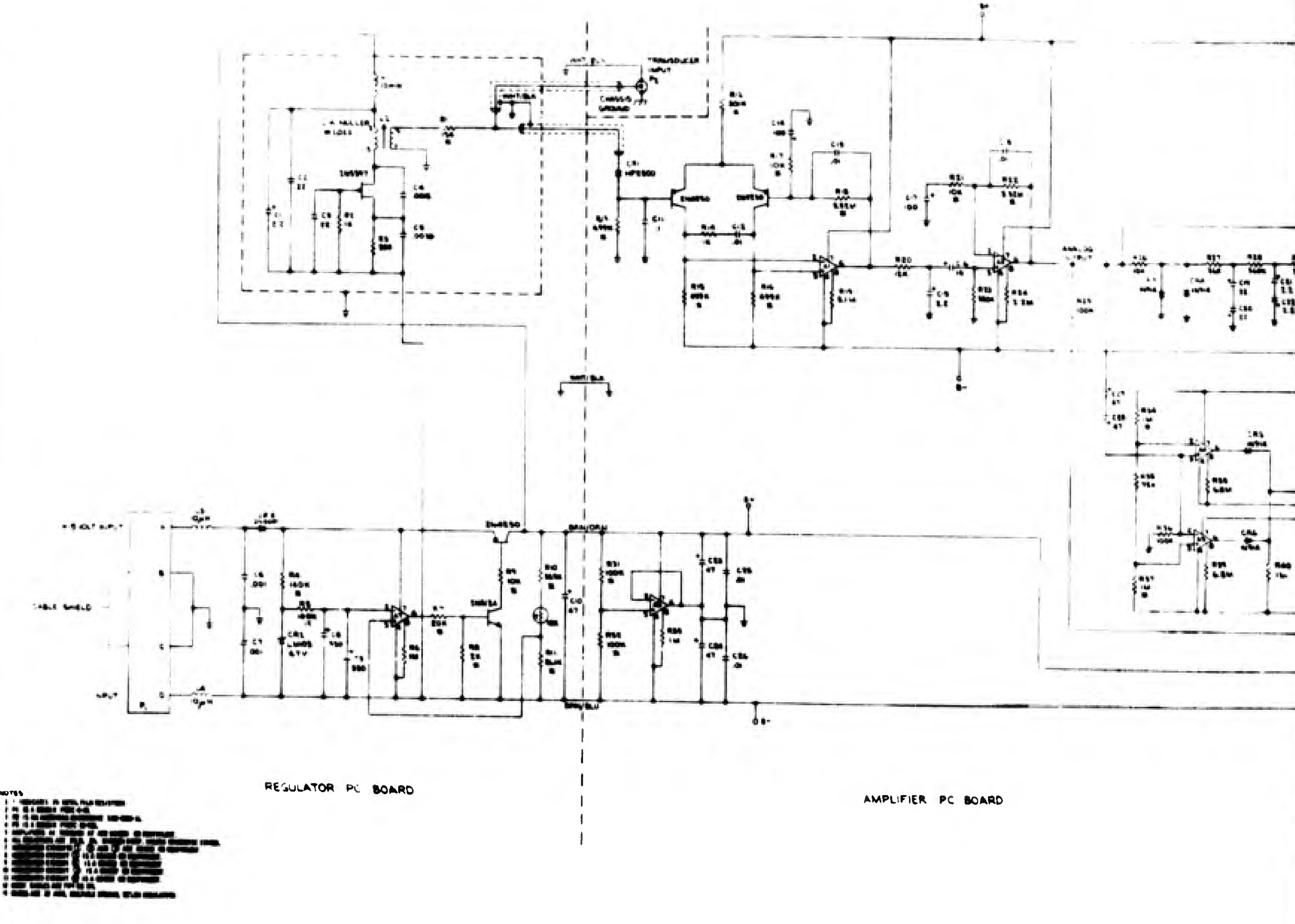
Figure 41. Zero Crossing Logic Schematic

APPENDIX

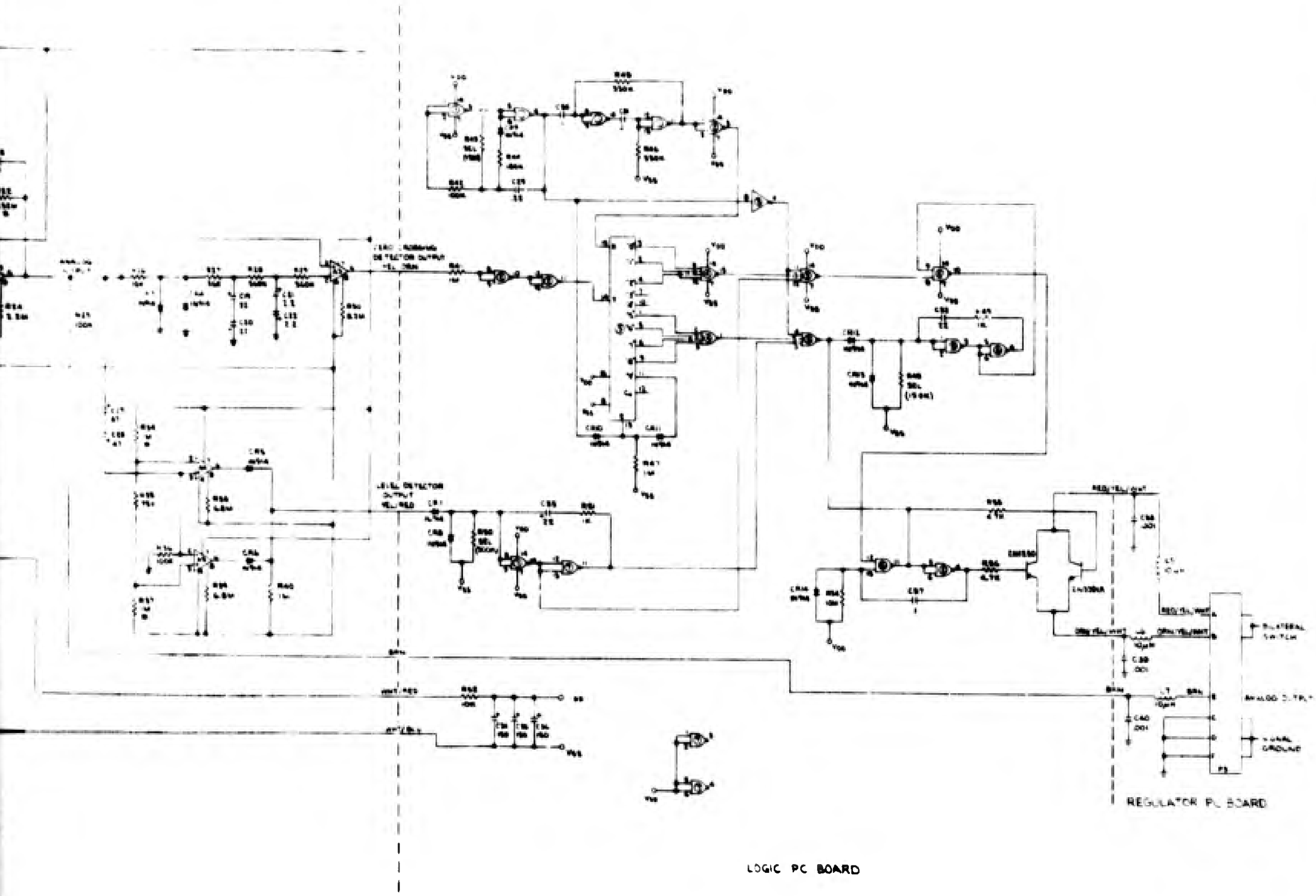
SYSTEM SCHEMATICS



Transducer Assembly Schematic



Electronics Assembly Schen



tronics Assembly Schematic

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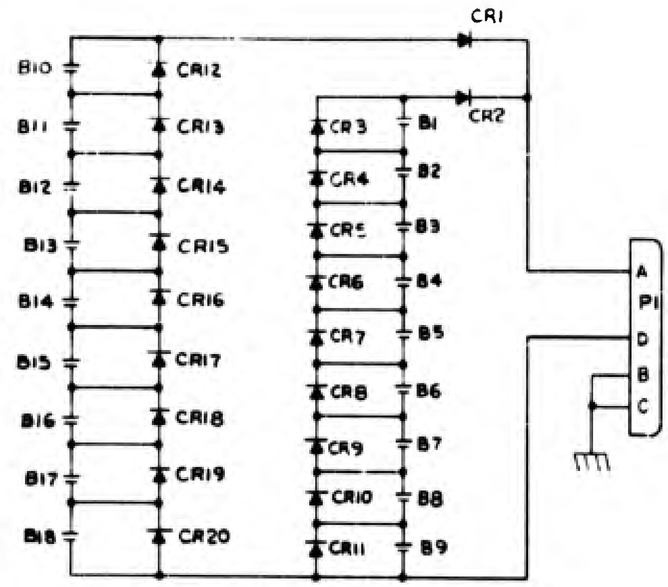
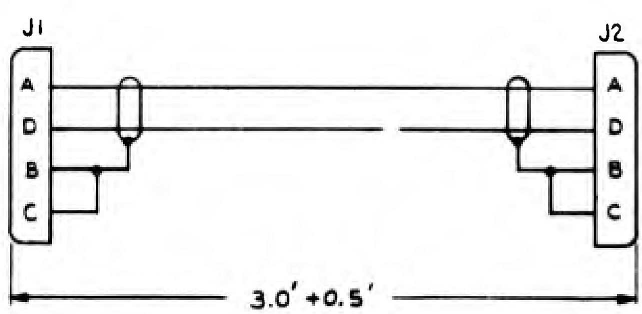


1 — EACH CELL IS 1.8 VOLTS D-C, #6 MAGNESIUM.
2 — DIODES ARE 1N4001.
3 — CONNECTOR IS A BENDIX PT07C-8-4S.

Battery Assembly Schematic



1 CONNECTORS ARE BENDIX PT06P-8-4P.

Cable Assembly Schematic

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