AN ELAPSED TIME INTERVAL COUNTER FOR SEISMIC EXPLORATION

by

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A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1962

APPROVED:

Redacted for Privacy

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Date thesis is presented Aug 18, 1961

Typed by Betty Anderson

ACKNOWLEDGMENT

The author is grateful to L. N. Stone, Professor and Head of the Department of Electrical Engineering at Oregon State University, for his helpful discussion and encouragement in this project. He would also like to express appreciation to James C. Looney whose help on circuitry was invaluable and to Dr. W. D. Wilkson for his suggestions and advice concerning the geophysical problems.

TABLE OF CONTENTS

LIST OF FIGURES

AN ELAPSED TIME INTERVAL COUNTER FOR SEISMIC EXPLORATION

INTRODUCTION

Seismic exploration of the earth's crust is based on the principle that sound or shock waves travel through the subsurface materials at varying speeds and along different paths. The speed of the seismic wave depends upon the density and rigidity of the material while the path is determined by the geometry of the subsurface layers.

This seismic exploration requires the accurate measurement of the time interval between the generation and the detection of the seismic or shock wave. With this measurement it is then possible to determine information such as the depth, geometry and composition of the subsurface formations.

The equipment developed in the past for this type of exploration was designed primarily for petroleum prospecting which required measurements at great depths with high resolution and accuracy. Unfortunately, the equipment used in this type of exploration was not only expensive, but required a large number of highly trained personnel and considerable time to perform a single test. Therefore, the present equipment is not practical for engineering surveys designed for rapid, inexpensive and shallow exploration such as determining the depth to bedrock at sites for roads, buildings and other structures.

This thesis study dealt with the development and design of a portable time interval counter capable of performing these shallow engineering surveys.

SEISMIC PROSPECTING THEORY

The Seismic Reflection Technique

There have been two basic techniques developed for seismic exploration. The first is the reflection method and as its name implies, deals with the principles for the transmission of seismic reflected waves from the subsurface layers to obtain information on their depth and geometry.

The reflection technique is the most widely used method for seismic prospecting due to the detailed picture presented of the subsurface formations and the high degree of precision attainable for great depths. Due to these characteristics it has been extensively used and developed in the field of petroleum exploration. Here the depths of the different layers are determined by measuring the travel time of the seismic waves generated at the surface and reflected back from the formations below. With the knowledge of the seismic velocities for the various layers one can then calculate their depths and geometry.

In comparing the characteristics of the reflection method and the requirements which appear to be applicable and necessary in the development of a portable unit for seismic investigations, a number of discrepancies arise.

The reflection method requires the time interval measurement associated with the seismic wave reflected from the various horizontal interfaces. This is accomplished by either maintaining a continuous record of the reflected waves as a function of time or a means must be developed to separate and store a particular time interval measurement associated with each reflecting layer. This multi-event storage requirement and selection capability at once introduces problems as to size and cost in regard to a portable device.

The success of the reflection method depends on the accurate determination of the velocity for the various layers being investigated. Usually these velocities are unknown and accurate determination can only be made by well logging or other involved methods which are costly and time consuming.

Last, but probably the most important is the fact that the reflection method produces inferior results at shallow depths with closely spaced interfaces which are of great importance in engineering surveys. This is due to the fact that it is impossible to distinguish the small time intervals associated with these closely spaced interfaces.

A continued investigation of the reflection technique as far as accuracy and simplicity leads to the conclusion that this method is not suitable for use in the design of a portable seismic unit for engineering type applications.

The Seismic Refraction Technique

The second method used in seismic prospecting is the refraction technique. This technique is the least-used method today due to the smaller scale at which the subsurface layers are detailed. On the other hand this method has a number of important advantages over the reflection method in regard to its use for shallow engineering surveys.

The refraction technique makes possible the identification of the subsurface layers in the cases where no previous information is available on the subsurface geology. This means that no prior knowledge as to the velocities of the subsurface layers need be known in the interpretation of the refraction data. In fact the refraction method produces data on the velocity of the various formations as well as on their configuration thus enabling one to identify the composition of the formations being mapped. This method requires the measurement of only the first arrival times for the seismic waves and therefore eliminates the need for storage of later intervals associated with the reflection method. The refraction method works particularly well in areas where a high velocity layer is overlain by a lower velocity formation. This case is predominant in engineering studies where the bedrock layer is overlain with topsoil and highly weathered materials.

The refraction method of seismic exploration can best be explained by considering a hypothetical two-layer investigation. This case has two horizontal layers of uniform velocity V_0 and V_1 with the interfaces separated by a distance h_1. The velocity of propagation V_1 of the lower bed is assumed greater than V_0 of the upper bed. This increase in velocity with depth is a necessary condition for all refraction studies.

Figure 1 shows the time-distance curve and the ray paths of the least travel-time for this investigation. This curve, which represents the elapsed time interval of the first seismic event as a function of shot-detector distance, is the most convenient method for interpreting refraction data. With the information presented by this curve it is possible to calculate the depth and velocity of subsurface formations for a refraction study whether it be a shallow engineering problem or a deep geophysical investigation.

If a seismic wave is generated at the shot point S_1 on the surface, the energy will be transmitted to the detector at point O by a spherical expanding wavefront. When the shot-detector distance is small the wave SO traveling horizontally in the upper medium will produce the first

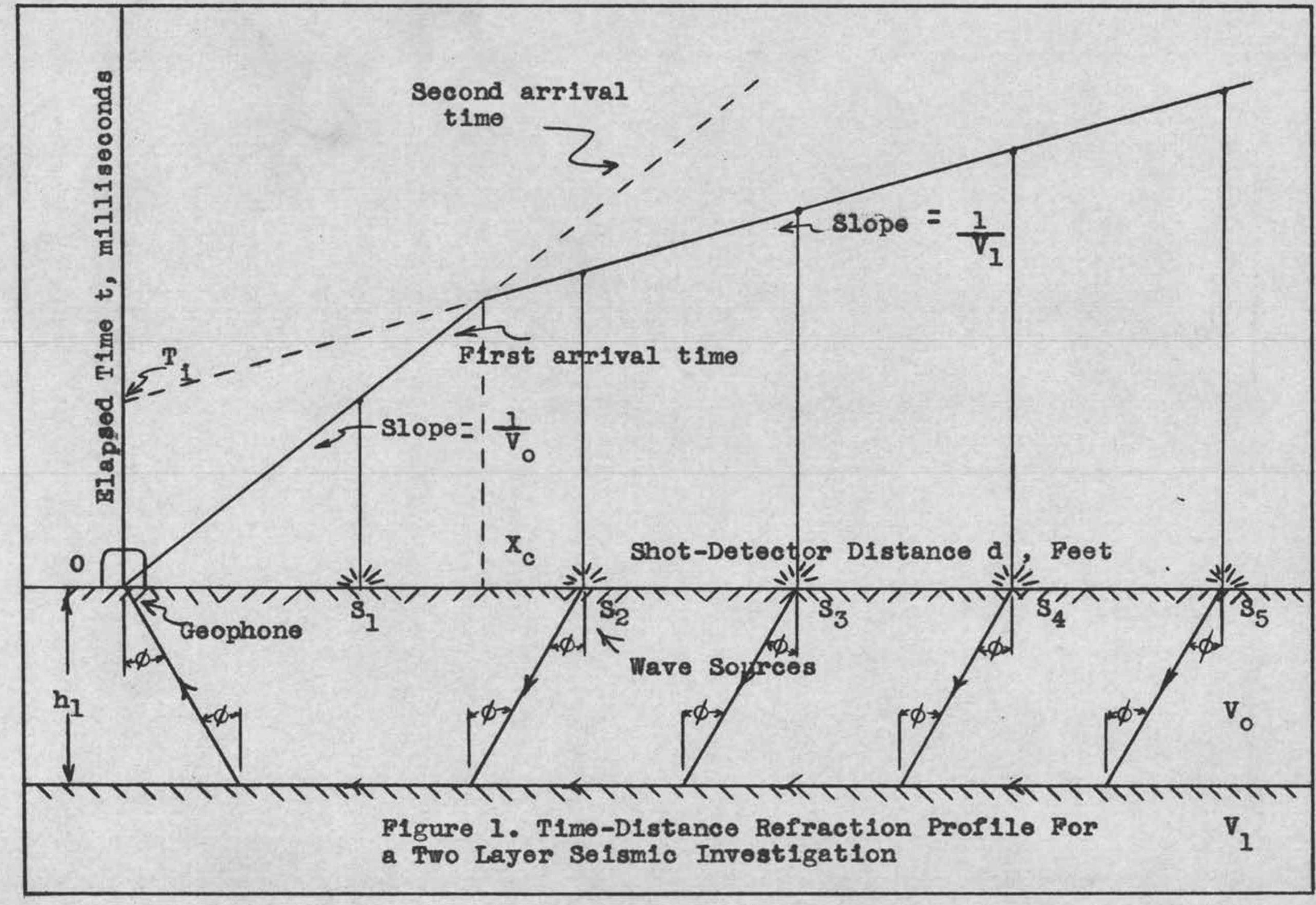


Figure 1. Time-Distance Refraction Profile For a Two Layer Seismic Investigation

detected seismic event at the geophone. However, when the shot-detector distance d becomes large, the wave which is refracted on the lower horizontal interface of higher speed will overtake the direct surface wave.

The wave which is refracted into the lower medium due to the velocity of propagation change is similar to light rays in that it acts according to Snell's law. The form of Snell's law which is particularly useful in this case is given in Equation (1).

$$\frac{\sin\phi}{\sin R_1} = \frac{V_0}{V_1} \tag{1}$$

Here ϕ is the angle of incidence, R_1 the angle of refraction with V_0 and V_1 the respective velocities of the two layers.

A study of the geometry for problem produces a minimum refracted travel-time at the point where the angle of refraction becomes 90°. This point produces a critical angle of incidence ϕ_c whose sin is equal to the ratio of the velocities for the two layers. This angle is of great importance in refraction work since it describes the path of the refracted wave with the least travel-time. This means that the first-arrival, refracted, seismic wave does not penetrate the second medium but travels along the interface with the velocity V_1. The wavefront of the refracted wave at the interface introduces new disturbances in the upper layer due to its oscillating stress. This develops a new wave in the upper layer which has a ray that returns to the surface at the critical angle. This action is described by the path of least travel-time for the refracted wave as shown in Figure 1. For shot-detector distances greater than the critical distance x_c it can be shown that the first arrival seismic event is produced by the refracted instead of the direct surface wave.

With the time-distance data, several applicable equations and a graph will provide information on the depth of the layers of different density materials and the speed of the waves. These depth equations in terms of both intercept time and critical distance are derived in the appendix for the two layer case. The results are summarized below in Equations (2) and (3).

$$h_1 = \frac{T_i}{2}\sqrt{\frac{V_1 \quad V_0}{V_1{}^2 - V_0^2}} \qquad (2)$$

in terms of critical distance X_c

$$h_1 = \frac{X_c}{2}\sqrt{\frac{V_1 - V_0}{V_1 + V_0}} \qquad (3)$$

In concluding the discussion on refraction one can see that the main problem is the detection and measuring of the elapsed time interval associated with the first-arrival seismic event. With this information a classification and identification of the subsurface materials can be easily made.

SYSTEM DESIGN

Basic Requirements

The theory for both seismic reflection and refraction prospecting methods suggests certain requirements necessary for the equipment used. These basic requirements apply to both portable units for shallow engineering surveys and elaborate equipment necessary for precision oil or geophysical investigations. These requirements can be summarized as follows:

1) First there must be a means for generating the seismic waves at the earth surface. There must also be some connection with the shot point to indicate the exact instant at which the seismic wave was generated.
2) There must be a method for detecting the reflected or refracted seismic waves from the subsurface interfaces.
3) There must be a means of relating the series of seismic events with some precise time measurement.
4) The recorded seismic information must be presented in a form useful for rapid and accurate interpretation.

The problem involved in this system design was the combination of all these features into an inexpensive device of minimum size and complexity which would perform accurate seismic refraction investigations for engineering applications.

Seismic Wave Generation

The most common method of performing refraction investigations is the elapsed time interval measurement of the first-arrival event as detected by a series of geophones located at uniformly spaced intervals from a single seismic source. For a complete test this procedure requires only one seismic shot which is usually generated by an explosive charge. However, due to the restrictions placed on the design of this portable unit, the series of geophones had to be replaced by a single detector. This modification reduced the circuit operation to the monitoring of a single geophone with the measurement and storage operation reduced to that associated with a single time interval.

Therefore, in order to obtain the same amount of information this modified procedure required additional seismic sources equal to the number of eliminated geophones. The use of explosives for generating these seismic waves becomes undesirable due to high cost and the dangers of blasting even small shots in the proximity of men and equipment.

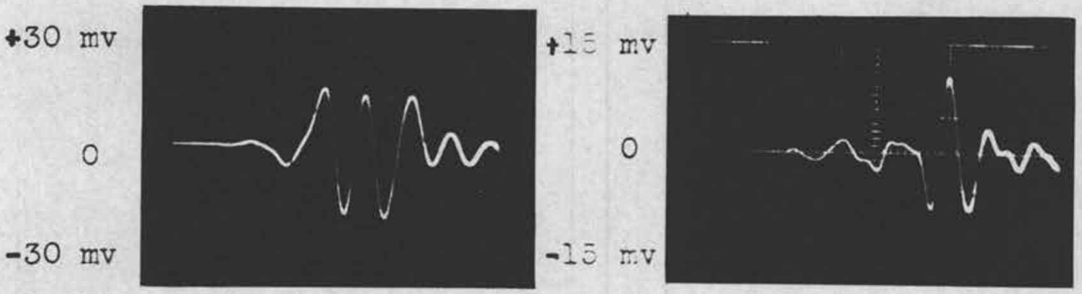
Fortunately, the majority of these engineering surveys require investigations at no more than 100 feet in depth which can be performed with small sources of energy. It has been found that a sledge-hammer blow on the ground is adequate as a source of energy in these applications (2, p. 311-333). An investigation of the seismic waves produced by this method are shown in Figure 2.

The amplitude of these detected seismic waves was sufficient to operate an interval counter if they were refracted from subsurface formations. The elapsed time interval associated with the first seismic event indicated a refraction from subsurface interfaces at shot-detector distances greater than 25 feet.

Associated with the generation of this seismic wave is the indication of the shot moment required for the measurement of the total elapsed time interval. The system design employed an inertial switch located on the handle of the sledge-hammer to generate this shot-moment signal. This method produced a reliable signal at the moment of impact for the sledge-hammer with only a fraction of a millisecond delay.

Designed Time Interval Counter

The resulting problem was the accurate measurement of the elapsed time interval of the seismic wave from its generation to first arrival detection and the representation



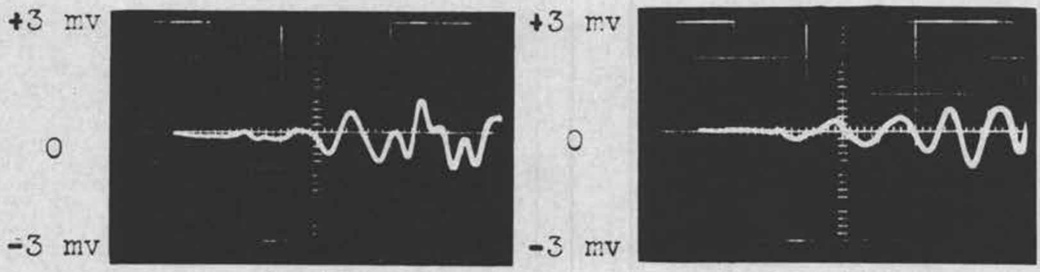
(2a)

Output Seismic Waveform
for a Shot-Detector
Distance of 10 Feet

(2b)

Output Seismic Waveform
for a Shot-Detector
Distance of 20 Feet

Note: Horizontal Scale is 5 millisecond per division for figure (2a) and 10 milliseconds per division for figure (2b).



(2c)

Output Seismic Waveform
for Shot-Detector
Distance of 50 Feet

(2d)

Output Seismic Waveform
for Shot-Detector
Distance of 75 Feet

Note: Horizontal Scale is 20 milliseconds per division for figure (2c) and (2d).

Figure 2

Oscillograms of Output Seismic Waveforms From a Standard Electromagnetic Geophone as Obtained for a 10 lb Sledge-Hammer Blow to a Metal Plate.

of this information in a form capable of rapid reduction or utilization without complicated recording and playback equipment.

There have been a few systems developed for this type of shallow engineering exploration (2, p. 311-333), but all appeared unsatisfactory due to their methods of supplying information and the complexity of operation. These systems used converted oscilloscopes with heavy lead-acid battery power supplies for the seismic wave display and modified radar techniques or calibrated sweep circuitry for the time interval measurement. These systems were not only semi-portable in nature but presented results which were based upon the operators skill and interpretation. The following system design differed from these systems in that it was completely portable and presented accurate as well as rapid results which did not depend upon this interpretation or skill.

The design of the time interval counter was based on a digital technique of measuring time. This counter allowed the first-arrival seismic event to control the digital counting of a precision time-base clock. This type of measuring system produces very accurate as well as reliable operation and lends itself very readily to modern semiconductor circuitry techniques. Figure 3 shows a block diagram of this system which can be broken down into the following basic subassemblies:

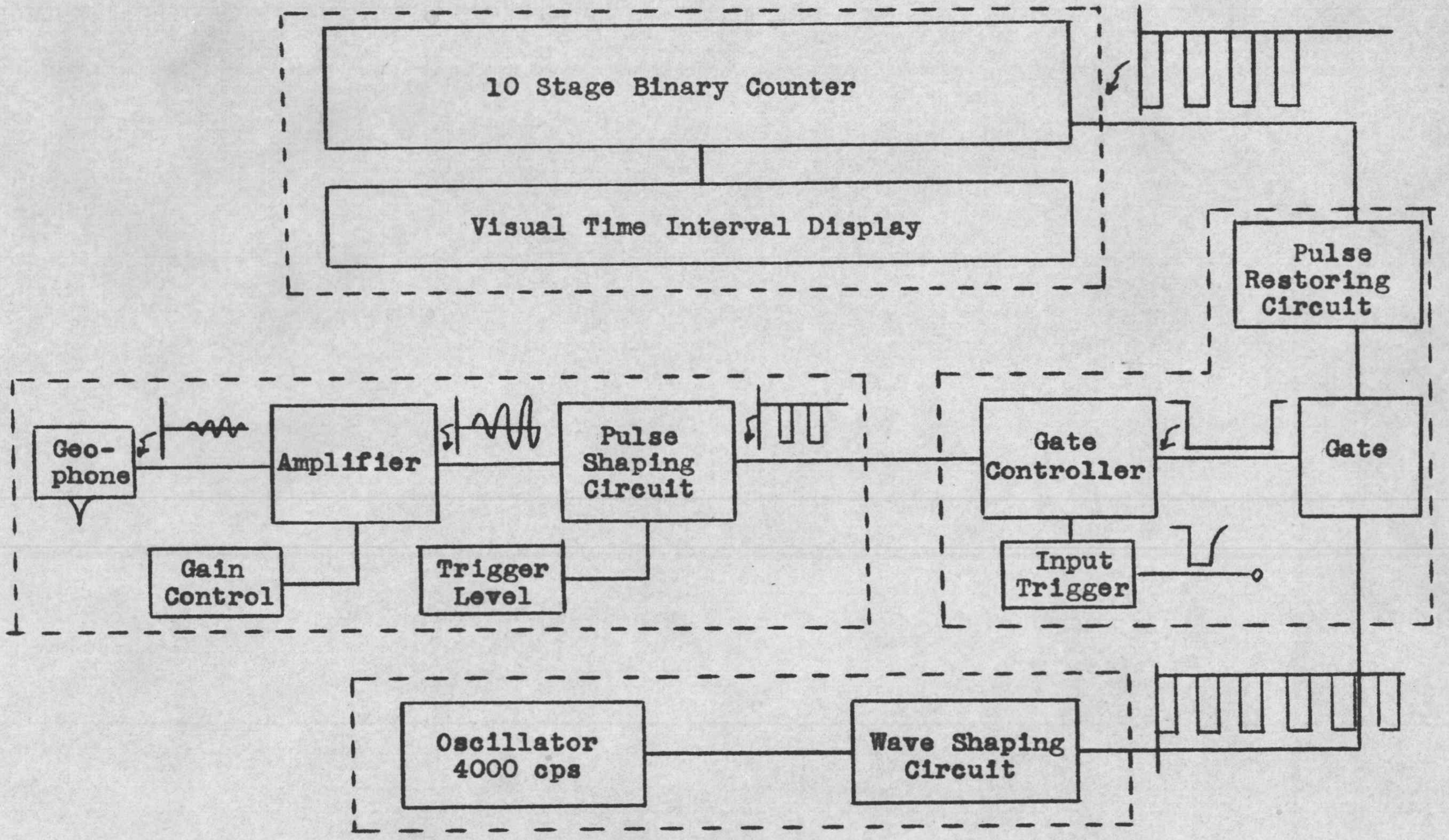


Figure 3. Block Diagram For the Time Interval Counter Showing the Four Basic Subassemblies.

1) Detection and Pulse Shaping Section
2) Gating and Trigger Section
3) Time Base Section
4) Digital counter and Readout Section

The detection section is composed of circuitry capable of detecting and accounting for the various amplitudes of the seismic waves produced in the numerous geological situations encountered. This section has to be designed to provide sensing of earth movement as small as 10^{-5} inches and account for both variation in ground level motion and transmission over a range of 100 to 1 (1, p. 40-67). Connected with this detection section is circuitry designed to convert the non-uniform seismic waves to square pulses capable of reliably operating the following gate section.

The gate section controls the flow of pulses from the time base generator to the digital counter and therefore determines the total time interval being measured. This gate is opened at the shot moment by a signal from the sledge-hammer allowing pulses to be transmitted to the output section where they are counted in a binary fashion and displayed by a series of neon lamps. On the reception of the first seismic event the gate is closed leaving the total measured time interval staticized in the output counter and available visually for an indefinite period.

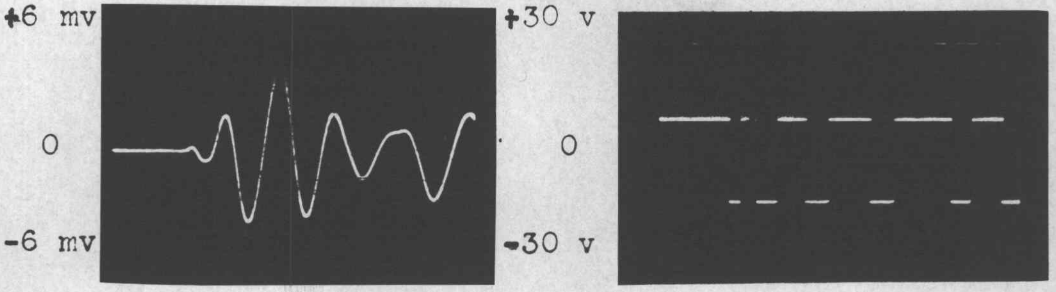
The pulses which are counted to determine the total elapsed time interval are generated by a precise time base section. This section, which is composed of a stable oscillator with a squared output, generates a continuous series of pulses while the system is in operation. However, only a small number of these pulses are counted to determine the given time as determined by the time the gate is open. This type of operation produces no fractional counts. The first or last pulse in a series may or may not pass through the gate. Thus there is an inherent possibility of a plus or minus one count error which would be a maximum of 0.25 milliseconds in any reading for the particular timing frequency of 4000 cps. The amount of error in any one reading varies depending upon the gate operation with respect to the series of timing pulses. One would then expect the amount of error to vary in a random nature since the gate is controlled by the sledgehammer blow.

Systems Operation

Figure 4 shows the oscillograms of the systems operation in performing an elapsed time interval measurement of 4.25 milliseconds. Due to the type of semiconductors used the logic and circuit operation is performed at or below ground.

Figure 4a shows the input seismic wave as detected by the geophone. The positive going phase which reaches a maximum value of 0.4 millivolts at 4.25 milliseconds represents the arrival of the first seismic event. It is this event which closes the gate terminating the measurement of a given interval. Figure 4b shows the squaring action of the pulse shaping section on the input wave. This circuit generates a 12 volt negative pulse of rapid rise time for each positive phase of the detected wave. This positive phase selection produced a uniform point of termination for each time interval measurement.

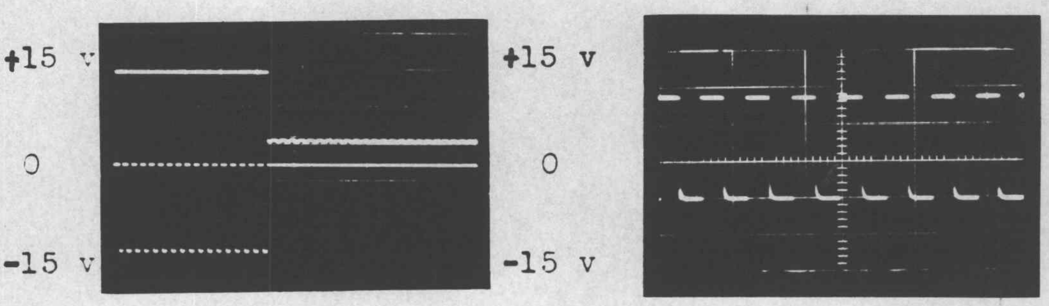
Figure 4c shows the output of the gate controller and the series of timing pulses transmitted to the output counter. The rise in the output of the controller from the initial inhibiting state of -10 volts to the enabling ground level at the shot moment is not visible in this oscillogram due to the method of sweep triggering. While the gate is in the enabling state, 17 pulses of 0.25 milliseconds duration are transmitted to and counted by the output section. This represents the total measured time interval of 4.25 milliseconds. It should be noted that the sweep speed is increased from 2 to 1 milliseconds per centimeter in Figure 4c and 4d in order to clearly show the timing pulses. The last oscillogram shows the output waveform for the time base generator.



(4a)
Seismic Wave at the
Output of the Geophone

(4b)
Output Waveform for
the Pulse Shaping
Circuit

Note: Horizontal Scale is 2 milliseconds per division for figures (4a) and (4b) .



(4c)

(4d)

Output Waveforms Showing
Both the Output of the
Controller and Input to
Counter

Output Waveform for
the Time Base Section

Figure 4

Oscillograms Showing the Circuit Operation for an Elapsed Time Interval Measurement of 4.25 Milliseconds by the Designed System

Note: Horizontal Scale is 1 millisecond per division for figures (4c) and (4d).

CIRCUIT DESCRIPTION AND OPERATION

The time interval counter uses transistors entirely due to their small size, low power requirements and inherent reliability. Saturated circuit design was used throughout in order to provide maximum reliability with changes in temperature, component values, and transistor characteristics. Also, the circuitry is designed for reliable operation in the worst-case condition where resistors, operating voltages and transistor parameters are all simultaneously at the extreme limit of their tolerances.

Since the completed system had to perform reliably in the field as well as the laboratory, extensive tests were made on the circuitry to ensure that certain minimum performance specifications would be met. These specifications include operation to at least 60°C with a 20 per cent reduction in supply voltages and a transistor beta reduction of 50 per cent from their initial values.

The circuitry operated reliably for at least a period of one hour in a temperature test chamber to the minimum of 65°C at a 20 per cent reduction of design level supply voltages.

The circuit diagrams for the following subsections are given in the appendix along with the values of the circuit components and the designed operating voltage levels.

Amplifier Section

The amplification was provided by a four stage voltage amplifier which produced a minimum usable gain of 150,000 ± 3 decibels from 20 to 15,000 cycles per second. This gain combined with the trigger circuit sensitivity produces operation of the counter with a signal of one microvolt from the geophone.

The transistor amplifier uses the grounded-emitter configuration combined with current feedback and bias stabilization to provide a high degree of temperature stability. Also, special low-noise transistors are used in the first three stages in an attempt to obtain high amplification at a relatively high signal to noise level. This results in a maximum equivalent noise input signal of 0.5 microvolts peak to peak with the input grounded.

Due to the fact that seismic signals obtained in the refraction method are of limited frequency range, an investigation was performed on the systems operation with band-limited amplification. However, this tuned amplification provided little or no improvement in the operation and therefore was not included in the completed time interval counter.

Variable gain adjustment is provided by controlling the negative feedback from the third stage collector to the second stage emitter. In addition to this variable gain adjustment, a fixed gain control exists which provides for the removal of the last stage of amplification from the circuit.

An emitter follower stage is connected to the output of the amplifier in order to produce an impedance match with the following Schmitt trigger circuit. This eliminates the deterioration in the gain of the amplifier due to the small load impedance presented by the trigger circuit.

Pulse Shaping Section

The section following the amplifier is designed to reshape the input signal into a form capable of reliably triggering the gate section. This function is performed by a Schmitt trigger circuit capable of assuming two stable states dependent upon the input voltage level. If the output of the amplifier is below a predetermined level, no trigger output exists. On the other hand, if the signal rose above this level, the circuit state will change producing a signal of fixed amplitude with a fast rise time. This action converts the various shapes of seismic waves with slow rise times to pulses of 12 volts amplitude with a rise time of less than 1.0 microsecond.

This circuit produces the squaring action and provides a means of controlling the sensitivity of the system. This operation is accomplished by controlling the level at which the seismic wave operates the trigger circuit. This controls the trigger action from signals as small as 25 millivolts to those as high as 2.5 volts.

Gate Section

The gate section consists of four basic parts. These include the diode AND gate, a pulse restoring circuit, the gate multivibrator, and the input trigger multivibrator.

The diode AND gate controls the counting operation in this device and is designed for positive-going, negative signals with an inhibit level of -10 volts and an enabling level at ground. Pulse deterioration was encountered in this gate due to the series dynamic resistance of the diodes and the capacitance located in its output circuitry. To overcome this effect a pulse restoring circuit is located between the output of the gate and the input to the counter section. This circuit consists of a saturated amplifier stage with RC compensation at its input. This capacitive overdrive increased the rise time of the timing pulses from 15 to 0.8 microseconds and provided reliable triggering of the output counter.

The gate controller is an R-S type saturating flip-flop which provides the inhibit and enabling signal for the diode AND gate. This flip-flop is set to the enabling state by the shot-moment signal and reset to the inhibiting level by the shaped seismic wave. The trigger multivibrator is similar in design and is used to prevent the retriggering of the gate controller by the contact bounce encountered in the operation of the shot-moment switch. This circuit prevents the destruction of a time interval reading by the movement of the sledge hammer.

Time Base Generator

The time base generator or frequency standard section consists of a tuning fork oscillator followed by a Schmitt trigger shaping circuit. The oscillator is composed of a feedback amplifier with a tuning fork resonator as the frequency controlling device. The fork resonator is temperature compensated with bimetal construction and provides an overall accuracy and stability of 0.05 per cent from -55°C to 85°C at a frequency of 4000 cycles per second.

The tuning fork resonator has a loaded Q greater than 10,000 and was selected as the frequency controlling device due to the high stability it produces with transistor circuitry at this low 4000 cps. frequency. The only comparable frequency stabilization method available is a temperature controlled quartz crystal. However, stabilization by this method would have required an oscillator frequency of at least 100,000 cps which would have necessitated additional dividing circuitry in the output section. The additional circuitry plus the high cost of the temperature stabilized crystal oscillator made this method impractical in this system.

The frequency of 4000 cps was selected as a compromise between required accuracy, output counter circuitry and availability of the tuning fork resonator. This frequency provides measurements in time to within ± 0.25 milliseconds which is adequate for any engineering application encountered.

The 50 per cent clipped and 15 per cent dissymmetrical sinewave output was converted to a reliable square wave triggering source by a Schmitt trigger circuit. This action results in a 12 volt output with a rise time of 0.9 usec.

Output Section

The output section consists of a ten stage binary counter with a total time interval of 255.75 milliseconds. This interval was found to be adequate for seismic measurements in low velocity formations to a depth of 200 feet.

The basic binary flip-flop or multivibrator used in this counter chain is a saturating transistor device capable of operation to 75,000 counts per second with fixed amplitude triggers. This flip-flop operates with a saturated collector current of 2.15 ma. per collector, dissipating 26 milliwatts per stage. This circuit is not fast in terms of modern high speed saturated devices, but is more than adequate for the 4000 cps clock rate encountered. This saturated operation is in keeping with the reliability aspect in that it provides performance almost completely independent of the supply and transistor parameter changes.

The entire chain of 10 flip-flops demonstrated reliable operation with both pulsed and continuous trigger signals between the relatively wide supply voltage limits of 6 to 20 volts at a temperature to 75°C. To further improve the triggering reliability steering AND gates are provided at the inputs to each multivibrator.

In order to visually represent the total measured time interval, neon indicator lamps are connected to the flip-flops and indicate their static states.

EXPERIMENTAL RESULTS

Equipment Configuration

Figures 5 and 6 represent the completed equipment configuration as used in these performance tests. Figure 5 shows the front panel layout with the controls necessary for the system operation while Figure 6 shows the location of the major portions of the circuit. There was no attempt at miniaturization in the construction, but the complete system including batteries is very portable and can be carried by one man. The dials located with the trigger level and gain control are for reference only, with the minimum values being in the extreme counter clockwise position.

Operating Procedure

The operating procedure developed for the use of the time interval counter in a seismic exploration is as follows. A traverse over which the investigation is to be made is selected, keeping in mind the geological terrain and its effect on the measured results. Shot points are then laid out along this traverse at equal intervals at predetermined distances from the detector. For very detailed work, short intervals of 5 feet can be taken. However, 10 foot intervals produce adequate results in most instances. The geophone is located as far away as

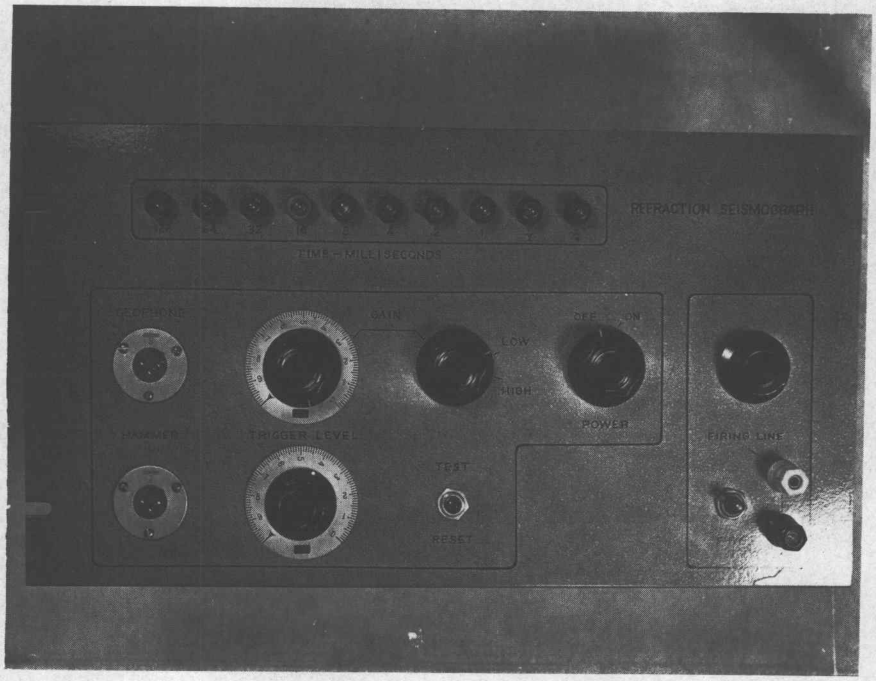


Figure 5

Front View of the Completed Time Interval Counter Showing the Controls Necessary for Its Operation.

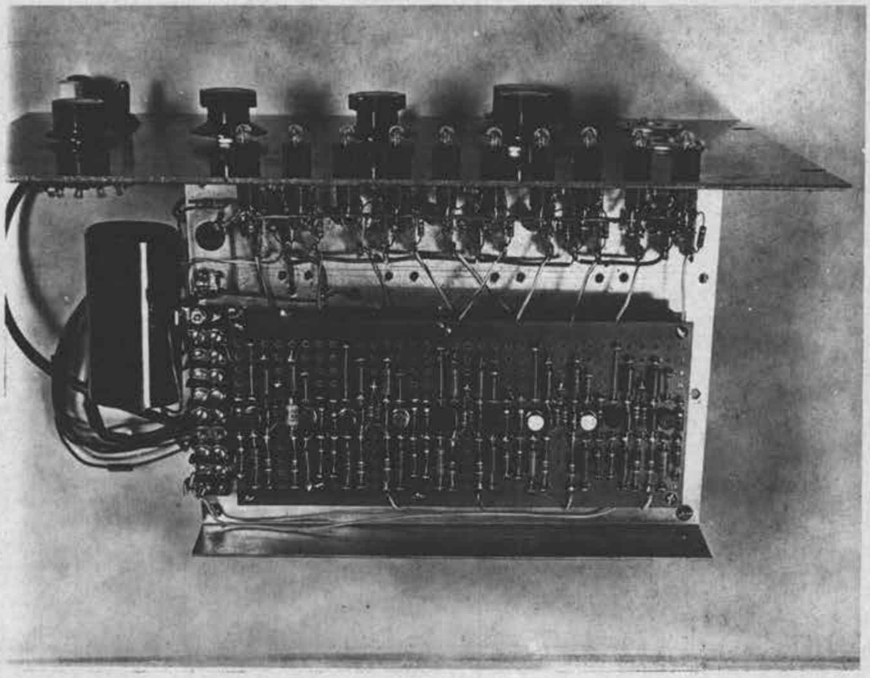


Figure 6a. Side View of the Time Interval Counter Showing Circuitry of the Binary Counter and Neon Display Unit.

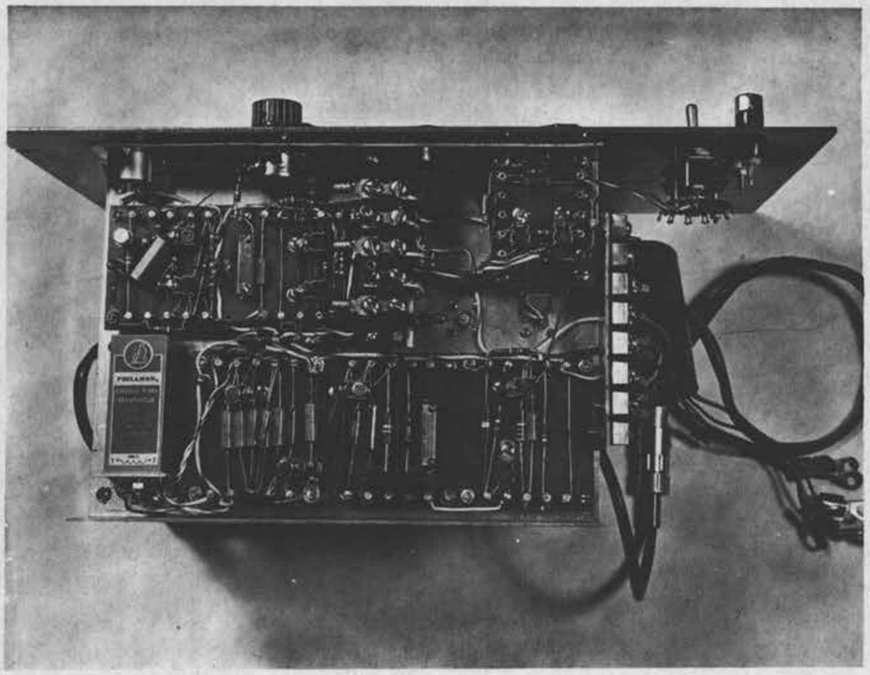


Figure 6b. Side View of the Time Interval Counter Showing the Circuitry of the Trigger, Wave Shaping, Gate and Time Base Sections.

possible from the counter to prevent interference by the movements of the operator while the tests are being conducted.

The counter is then set at the point of maximum signal detection sensitivity. This point is determined by manually opening the gate with the test control and then rotating the trigger level control clockwise until the counting of the time base generator stops. At this point the counter is triggered by either the ambient ground noise or that generated internally in the amplifier. The sensitivity is then decreased slightly, producing operation with the trigger level located just above the noise which is the point of maximum signal detection.

The seismic waves are then generated at the shot points by striking a 6-in. square by 1-in. thick steel plate with a 10-lb. sledge-hammer. The use of this plate provides a means of coupling the energy to the ground as well as preventing the sledge from sinking into the soft topsoil. Several readings were taken at each location to ensure that the plate is firmly seated and that consistent readings are being obtained.

Time interval measurements are then taken for each of the shots in a given traverse. A set of data is obtained at successive shot points while working away from the geophone. This procedure facilitates the plotting of the time distance check curve which is desirable in a number of the more involved tests.

Preliminary Performance Tests

A number of preliminary laboratory tests were performed on the completed system prior to actual field use. These tests were designed to simulate the system operation and to ensure that the circuitry is operating properly. All tests were performed with the system battery power supply to ensure that actual operating conditions were being met.

This system is a time measuring device whose accuracy is dependent upon that of the time-base generator. Thus the first test was designed to determine the accuracy and stability of this section under severe operating conditions. The frequency of this section was measured with a Hewlett Packard Electronic Counter Model 524C. In order to obtain the highest accuracy, all measurements represented a 10 second average. Under normal operating conditions at room temperature with supply voltages at their nominal levels, a frequency of 3,999.8 ± 0.1 cycles per second was measured. This frequency was measured for sinusodial and square wave outputs. This represents a deviation from design frequency of no more than 0.005 per cent, and lies within the 0.05 per cent tolerance set by the design. The increase in temperature to 55°C and a reduction of 50 per cent in the supply voltage level had no effect on the frequency of operation.

The second test employed a monostable multivibrator with a phase inversion circuit to simulate the action of the gate controller in a time interval measurement. The variable period adjustment of the monostable multivibrator allowed the simulation of various time interval measurements and provided a means of testing the accuracy and operation of the output counter section. The results as measured by both the 524C counter and the designed system checked to within the ± 0.25 millisecond error dictated by the theory of the gates operation.

The last preliminary test involved a number of time interval measurements in an actual seismic investigation on the campus at Oregon State University. Since there was no means of determining the actual depth and geometry of the subsurface formations, the results were used to test the consistency of the readings in the field and the effect of the various shot magnitudes as generated by the sledge-hammer.

The data taken for this investigation indicated uniform results with a deviation of no more than 0.5 milliseconds with a moderate blow to the ground. The time-distance curves produced by this data is shown in Figure 7. This linear distribution of the data as well

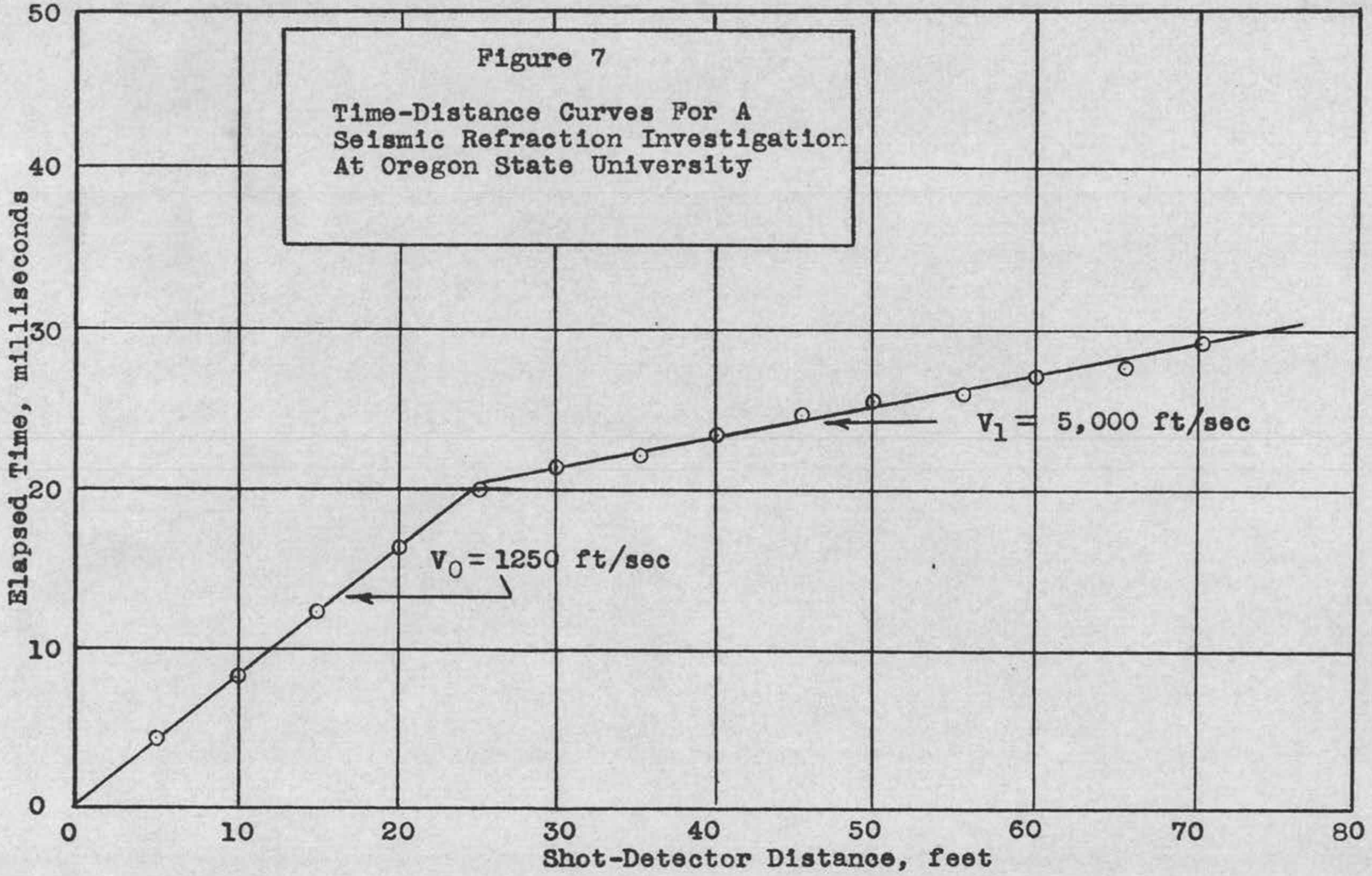


Figure 7

Time-Distance Curves For A Seismic Refraction Investigation At Oregon State University as the plausible results indicated proper operation of the device.

McMinnville Dam Site Test

The completed time interval counter was then tested in an actual civil engineering application. This involved the structural investigation of the subsurface material at a proposed dam site on the Nestucca River near McMinnville, Oregon. This location was selected not only for its engineering application, but because it provided a means of comparing the measured results with previously drilled boreholes. Also, tests were made at a roadway-cut to determine the actual velocity of the different materials at only a short distance from the test site.

The seismic test was performed on borehole number three located on the northeast bank of the dam site. The time distance curve obtained for this investigation is shown in Figure 8. The linearity of these curves indicates fairly consistent readings as well as a uniform velocity for the various layers. The three different slopes indicated three types of material. Intersection of the lines indicated two changes in consolidation and provided sufficient data for calculating the depths of two layers.

The seismic results as calculated by the depth equations indicated topsoil with a low velocity of 1300

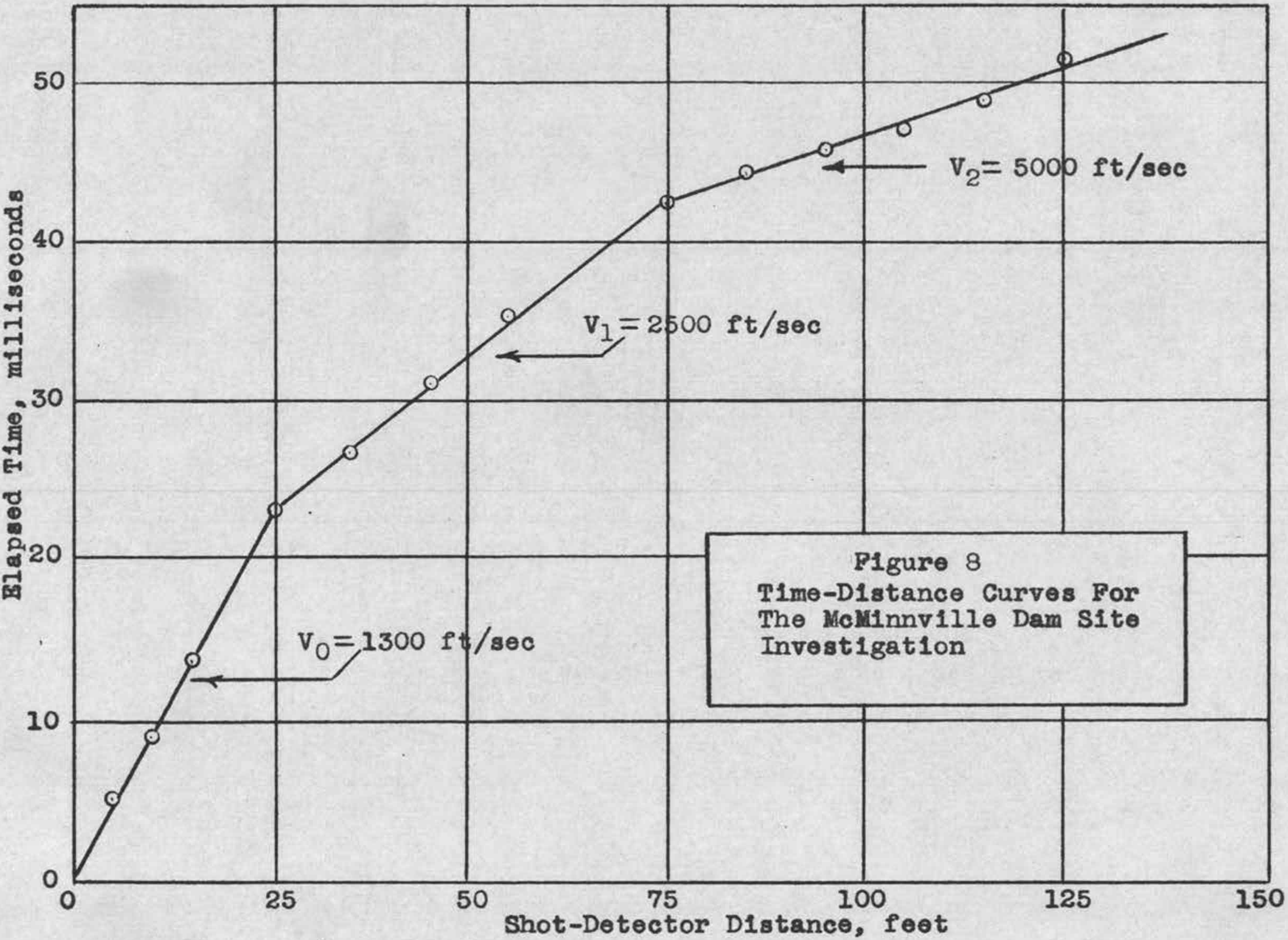


Figure 8
Time-Distance Curves For The McMinnville Dam Site Investigation

feet per second extending down 10 feet. Forty feet of deeply leached and spheroial weathered basalt lay below this topsoil, resting on jointed basalt at 52 feet. These seismic measurements checked very closely with the borehole and direct measurement. The results obtained for this investigation are summarized in Table I. The close correspondence between the seismic and measured results indicated proper operation of the system. Although the terrain over which this test was performed is far from ideal, the operation of the system under these conditions gave a good indication of the application of this system and the results which could be expected.

Seismic Velocity Table

In applications where no information is available on the subsurface geology, the refraction method yields data on the seismic velocities of the various formations and often makes possible their identification. This identification is facilitated by a table of seismic velocities as shown in Table II. The velocities obtained from the time-distance curves can then be compared with the table to identify the formations. However, caution must be used in this method due to the wide variation in velocities of the various subsurface materials produced by age, depth and physical condition. Thus, the results should be based not only upon the velocities, but upon

TABLE I

Measured Quantity \ Method of Measurement	Seismic Investigation	Borehole or Direct Measurement
Depth:		
1) First layer	10.75 ft	11 ft
2) Second layer	52 ft	53 ft
Velocity:		
1) Topsoil	1300 ft/sec	1300 ft/sec
2) Weathered Basalt	2500 ft/sec	2500 ft/sec
3) Jointed Basalt	5000 ft/sec	5000 ft/sec

TABLE II

Velocities of Seismic Waves in Various Formations

Material	Longitudinal Wave Velocity, ft/sec.
1. Unconsolidated Formations	
Marsh Land	500-1,000
Topsoil and Weathered Rock . . .	1,000-2,000
Gravel, Rubble, or Sand (dry) . .	1,500-3,000
Sand (wet)	2,000-6,000
Water	4,700-5,500
2. Consolidated Formations	
Clay	3,300- 9,200
Slate and Shale	7,500-15,400
Sandstone	6,000-13,000
Limestone	13,500-17,500
Basalt	12,000-20,000
Granite	13,100-18,700
Alluvium	1,640- 6,600
Salt, Carnallite, Sylvite	14,400-21,400

the surface geology and knowledge of the area being mapped. Most often a trained geologist is required in order to properly evaluate all the seismic results.

SUMMARY

The digital time measuring system produced very accurate as well as reliable elapsed time interval measurements for engineering seismic explorations. Due to the systems high resolution, it produced results which were comparable if not superior to those of conventional seismic equipment at shallow depths.

The use of semiconductors, a tuning fork resonator, and saturated design procedure in the mechanization of this system provide reliable and portable operation under severe operating conditions.

A sledge-hammer was found to be sufficient for the generation of seismic waves in shallow engineering applications where at least one high speed marker bed was overlain by a lower speed formation.

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APPENDIX

Derivation of Depth Equations

Two-layer Case

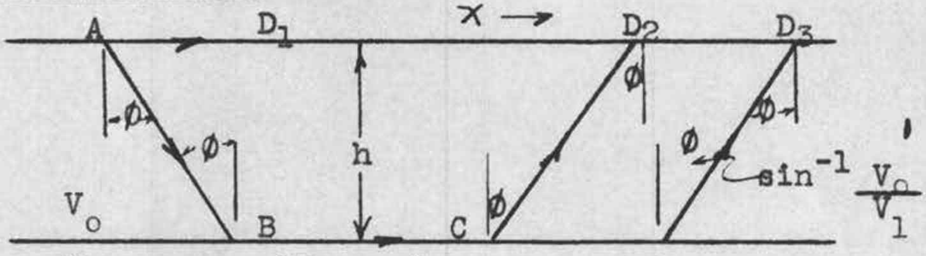


Figure 1

Ray paths of least time for a two-layer depth equation derivation.

The relationships between V_o, V_1 and 0 are,

$$\sin \phi = \frac{V_o}{V_1}$$

$$\cos \phi = \left(1 - \frac{V_o^2}{V_1^2}\right)^{\frac{1}{2}}$$

$$\tan \phi = \frac{\sin \phi}{\cos \phi} = \frac{V_o}{\sqrt{V_1^2 - V_o^2}}$$

Total time along the refraction path ABCD is,

$$T = T_{AB} + T_{BC} + T_{CD} \qquad \text{(a-1)}$$

Equation (a-1) can be written in the form

$$T = \frac{h}{V_o \cos\phi} + \frac{x - 2h \tan\phi}{V_1} + \frac{h}{V_o \cos\phi}$$

$$= \frac{2h}{V_o \cos\phi} - \frac{2h \sin\phi}{V_1 \cos\phi} + \frac{x}{V_1} \qquad \text{(a-2)}$$

Transformed to

$$T = \frac{2h}{V_o \cos\phi}\left(1 - \sin^2\phi\right) + \frac{x}{V_1} \qquad \text{(a-3)}$$

$$= \frac{x}{V_1} + \frac{2h \cos\phi}{V_o} \qquad \text{(a-4)}$$

$$= \frac{x}{V_1} + \frac{2h\sqrt{1 - (V_o/V_1)^2}}{V_o} \qquad \text{(a-5)}$$

which gives,

$$T = \frac{x}{V_1} + \frac{2h\sqrt{V_1{}^2 - V_o{}^2}}{V_1V_o} \qquad \text{(a-6)}$$

On the time-distance plot, this is the equation of a straight line which has a slope of $1/V_1$ and which intercepts the time axis (x 0) at the time

$$T_1 = 2h\,\frac{\sqrt{V_1{}^2 - V_o{}^2}}{V_1V_o} \qquad \text{(a-7)}$$

T_1 is known as the intercept time. (see Text figure 1)

The depth equation in terms of intercept time is as follows,

$$h = \frac{T_1}{2}\,\frac{V_1V_o}{\sqrt{V_1{}^2 - V_o{}^2}} \qquad \text{(a-8)}$$

The depth can be solved for in terms of the critical distance (X_c) by making use of the fact that the times $T_0 = \frac{h}{V_0}$ and $T_1 = \frac{h}{V1}\,\frac{2h\sqrt{V_1^2 - V_o{}^2}}{V_1V_o}$ are equal at X_c.

This results in the depth equation

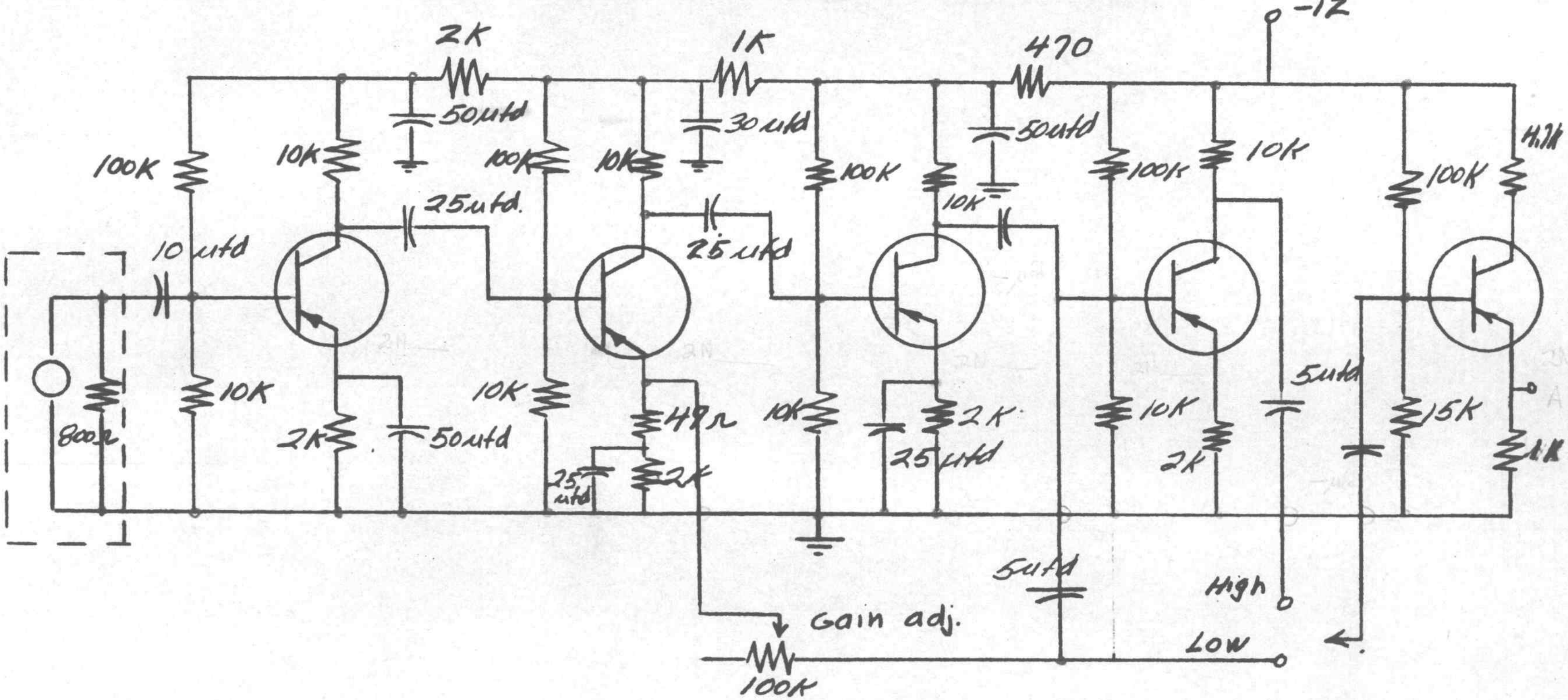
$$h = \frac{1}{2}\sqrt{\frac{V_1 - V_o}{V_1 + V_o}}\,X_c \qquad \text{(a-9)}$$

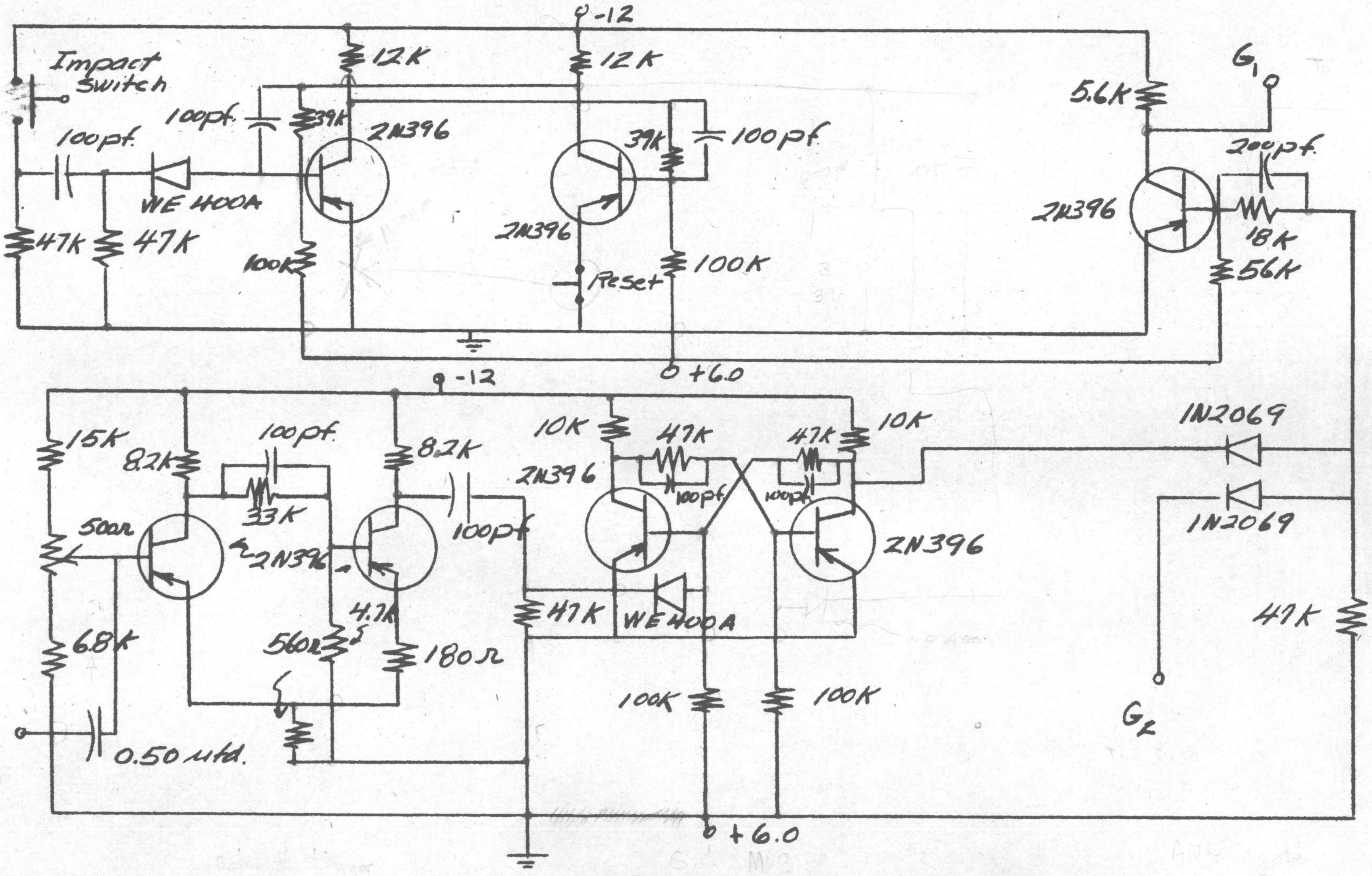
Three-layer case

The derivation of the depth equation oor the three-layer case is similar but somewhat more complicated. The results of this derivation are given by equation (a-10)

$$h_1 = \frac{1}{2}\left(T_{12} - 2h\frac{\sqrt{V_2{}^2 - V_o{}^2}}{V_2V_o}\right)\frac{V_2V_1}{\sqrt{V_2{}^2 - V_1{}^2}} \qquad \text{(a-10)}$$

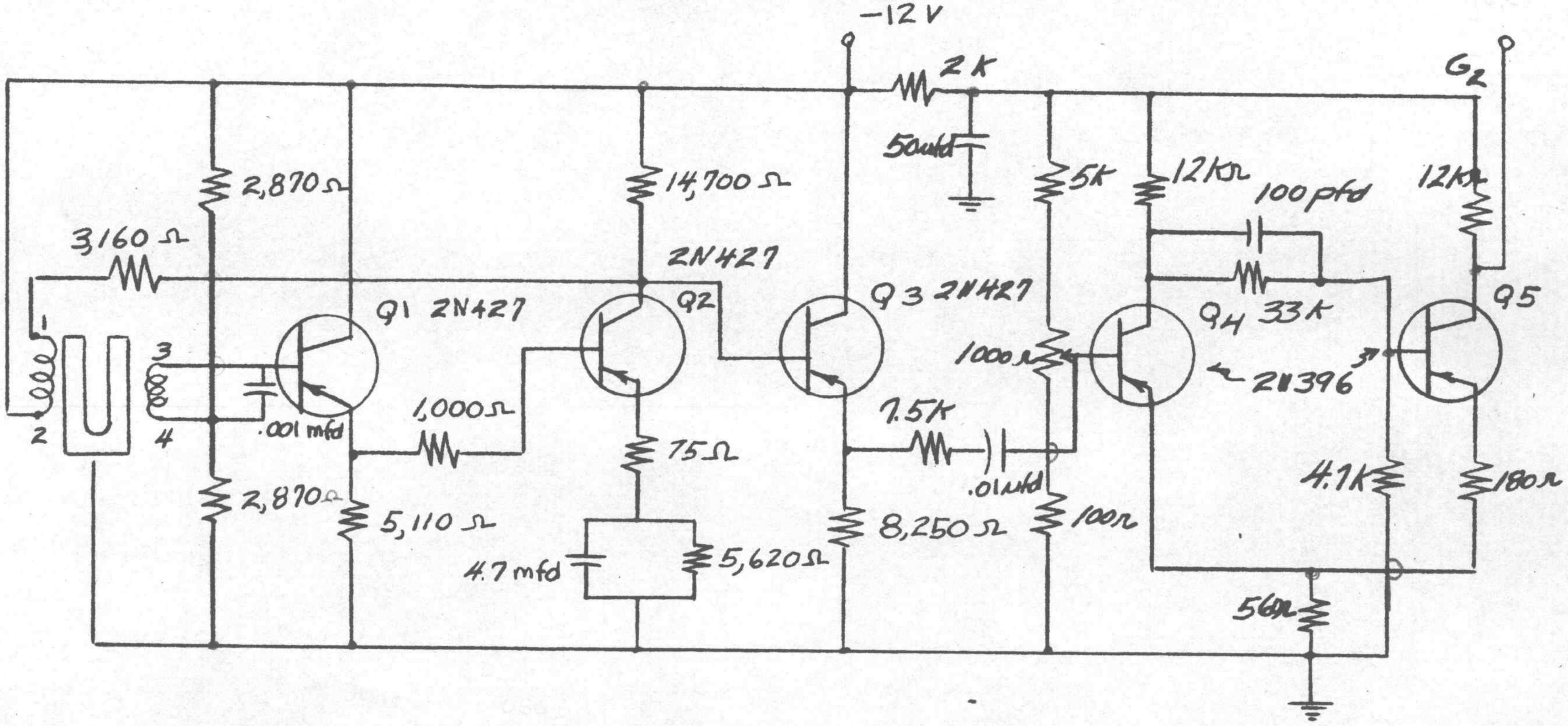
Circuit Diagram for the Four-Stage Amplifier with Cathode Follower Output



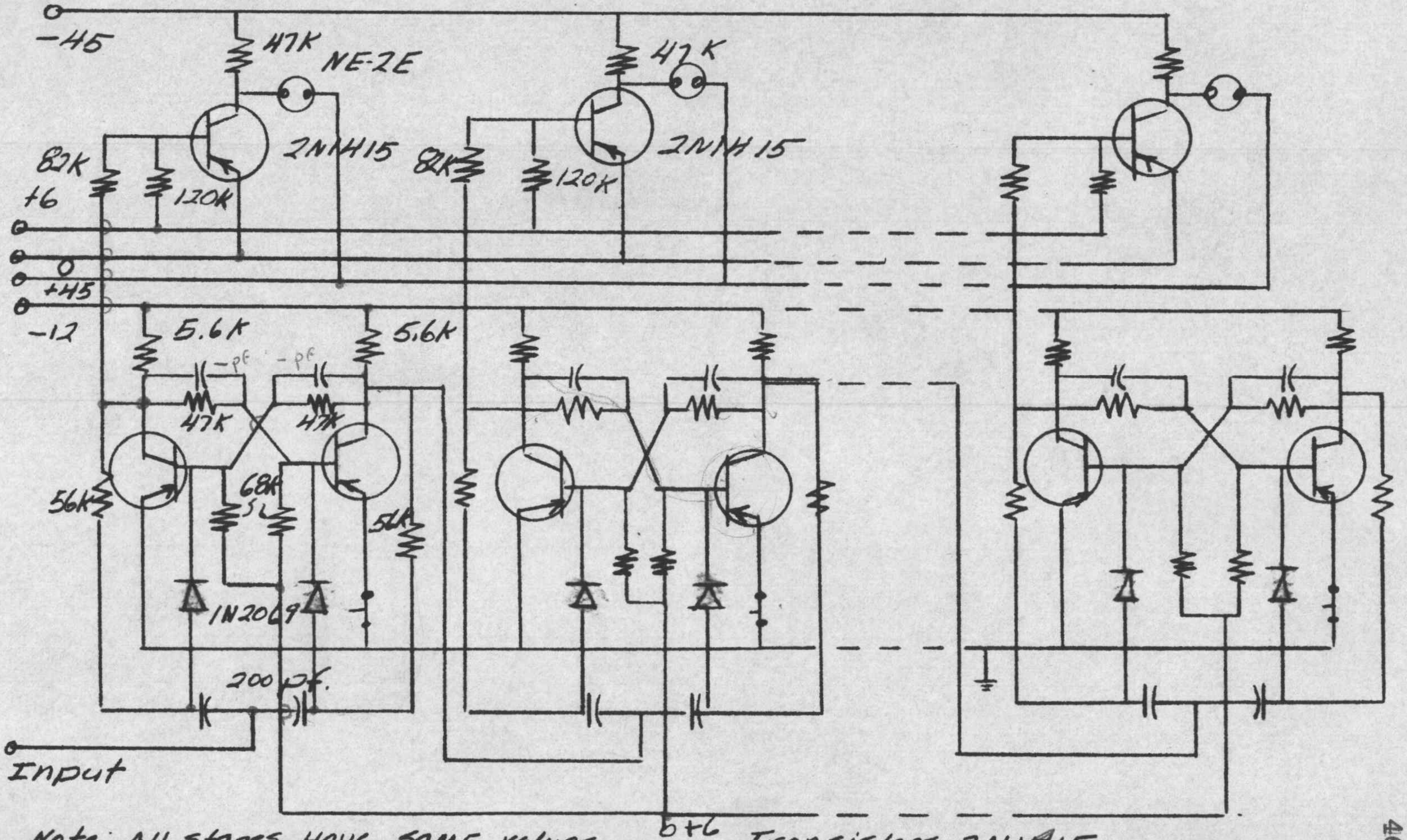


Circuit Diagram for the Gate Section

Circuit Diagram for the Time-Base Section



Circuit Diagram for the Binary Counter and Neon Display Section



Note: All stages have same values.

Transistors-2N1415