Final Report

APPLICATIONS OF ACOUSTICS IN THE MEASUREMENT OF COAL SLAB THICKNESS

By
W. J. Hadden, Jr.
J. M. Mills
A. D. Pierce
Co-Principal Investigators

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GEORGIA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL ENGINEERING
ATLANTA, GEORGIA 30332

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by

W. J. Hadden, Jr.
Assistant Professor

J. M. Mills
Assistant Professor

A. D. Pierce
Regents' Professor

T. Carolus
Research Assistant

Chew, C.-H.
Research Assistant

H. J. Venne, Jr.
Research Assistant

School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

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W. J. Hadden, Jr.
Co-Principal Investigator

A. D. Pierce
Co-Principal Investigator

J. M. Mills
Co-Principal Investigator

S. Peter Kezios, Director
School of Mechanical Engineering

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Chapter I

INTRODUCTION

The ultimate objective of the study described here is the determination of the possibility of employing acoustic waves at ultrasonic frequencies for measurements of thicknesses of slabs of coal backed by shale. The primary application envisioned is in monitoring coal-face thicknesses in longwall mining.[1] An essential subsidiary objective of this study is to obtain fundamental information concerning the acoustical properties (sound speed, attenuation rate, and characteristic impedance) of coal, and the relationship between these properties and the structural and compositional parameters used to characterize coal samples. Such information should guide the development of a theoretical model of wave propagation in coal, which would in turn be the basis for interpretation of results of experimental measurements and for the design of a slab thickness measurement system.

The progress toward these goals, summarized in this report, comprises: design and construction of a digital sine wave pulse generator; exploratory measurements of the sound speed and attentuation rate in coal at ultrasonic frequencies; development of analytical techniques for interpreting the data from both the exploratory experiments and projected

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[1]P. Britton, "Longwall Mining--Now there's a better way to get at the coal," Popular Science 211, No. 4 (1977), 118-21.

experiments which employ fully the capabilities of the digital burst generator; investigation of theoretical models of wave propagation in coal which can relate the experimentally determined sound speed and attenuation rate to physical properties of the medium. The choice of a suitable theoretical model is important so that numerical simulations of reflection from a coal-shale interface can be performed, and so that preferred frequency ranges and sensing techniques can be indicated, despite the sparsity of experimental data concerning wave speeds and attentuation rates.

Chapter II

DESIGN OF A TWO-CHANNEL SINE WAVE GENERATOR USING DIGITAL LOGIC CIRCUITS

by T. Carolus and J. M. Mills

2.1. Abstract

Description is given of a recently constructed device for use in ultrasonic experiments that employ two matched transducers. The device produces two sinusoidal bursts of substantially identical waveform, but with an adjustable delay between their starting times. The bursts are derived digitally from an external frequency standard (crystal clock), with a frequency of 5 MHz; the master frequency for sine wave synthesis can be any integer fraction of this clock frequency. The period of each cycle is ten times the reciprocal of that integer fraction of the master frequency. The duration of each burst can be adjusted, from one to nine periods of the waveform, in steps of one period. A delay counter is started coincident with the sinusoidal waveform generator. Upon completion of this preset delay interval, a second sine wave generator is started, which then generates the same number of cycles as there were in the first burst. The delay interval may be adjusted to any integer number of master clock cycles. Thus the two sine wave bursts can be delayed by an integer multiple of 1/10-th of a period of one sinusoid. The three-decade delay counters allow the total

delay between the two bursts to be as much as 99.9 cycles. Sinusoidal output frequency, the number of cycles in a burst, and the delay between two successive bursts are all adjustable during the course of an experiment.

2.2. Introduction

In order to measure the speed of sound in materials at ultrasonic frequencies, a pulser-receiver unit is often used. This unit generates a pulse, receives and amplifies its echo.

The disadvantages of using a pulse as a test signal are:

- The frequency spectrum of a pulse is not well defined;
- An exact phase control of transmitted and received signals is not possible;
- It is very difficult to determine exactly the beginning and ending of the pulse;
- The duration of the pulse is not adjustable.

To eliminate these disadvantages and to be able to use the technique of matched transducers,[1] which is based on an echo cancellation concept, a digital sine wave generator has been designed, built, tested and described as follows:

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[1] H. J. McSkimin, "A Method for Determining the Propagation Constants of Plastics at Ultrasonic Frequencies," J. Acoust. Soc. Am. (1951), 429-434.

2.3. Description of the "Digital Sine Wave Generator"

2.3.1. General Goals

The device should produce two sinusoidal bursts of substantially identical waveform, but with an adjustable delay between their starting times. The frequency of the sinusoids should vary from 100 KHz or less to 500 KHz. It should be possible to control very precisely the delay between the two bursts from 1/10 to approximately 100 periods of one sinusoid. The relative gain of the bursts should be adjustable.

In order to satisfy these goals, the device generates its output signals by means of digital logic circuits (CMOS integrated circuits), since it is comparatively easy to generate sine waves, frequency independent gates, etc., with simple logic circuits like FLIP-FLOP's, AND-, NAND-, and similar circuits.

2.3.2. The Main Components and How They Act Together

The main components (see Figure 2.1) are:

- The clock, which produces the master frequency, from which all pulses for generating the sine waves, gates, etc., are derived;
- The basic sine wave generator with amplifiers;
- The burst counters, which allow an adjustable number of pulses to pass to the sinewave generators such that the desired number of sinusoids for each burst is produced by each generator;

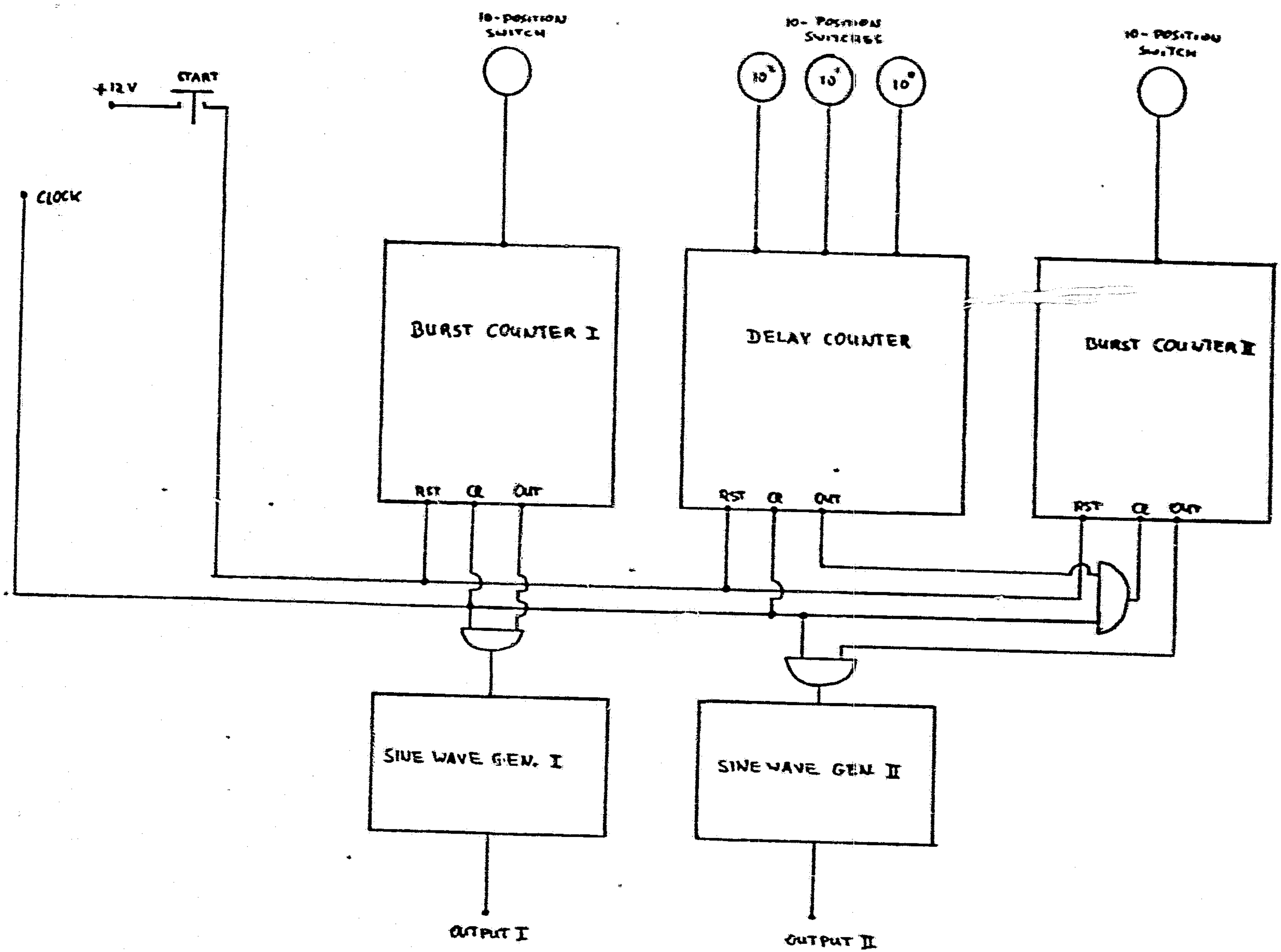

Figure 2.1. Digital Sine Wave Generator

- The delay counter, which starts the second burst counter and hence sine wave generator after an adjustable number of master clock pulses.

2.3.3. Description of the Components

2.3.3.1. The Sine Wave Generator. The design used (see Figure 2.2) is described in the "CMOS Cookbook."[1]

Out of five D-FLIP-FLOP's (4013) a modulo-ten, five stage walking ring counter is built. Four of the five phase shifted outputs are summed with carefully adjusted resistors (potentiometers R4 - R7) (Figure 2.3a). Though the waveform does not look like a sine wave, the first two spurious harmonics present are the ninth and the eleventh (-19.1 dB, -21 dB, respectively, Figure 2.3b), so it would be a simple matter to smooth the output with filters.

For the five stage generator, the output frequency is always 1/10-th of the clock frequency. Most CMOS circuits work with a maximum clock frequency of 5 MHz at 10 volts, power supply. Therefore, the maximum output frequency is approximately 500 kHz (as desired).

On the board, two identical sine wave generators are built.

Each output signal is amplified by an operational amplifier (CMOS 3140). The input offset is trimmable with pot R8 and the gain is adjustable with R9 (analogous for

[1]Don Lancaster, CMOS Cookbook, Howard W. Sams Publication (1977).

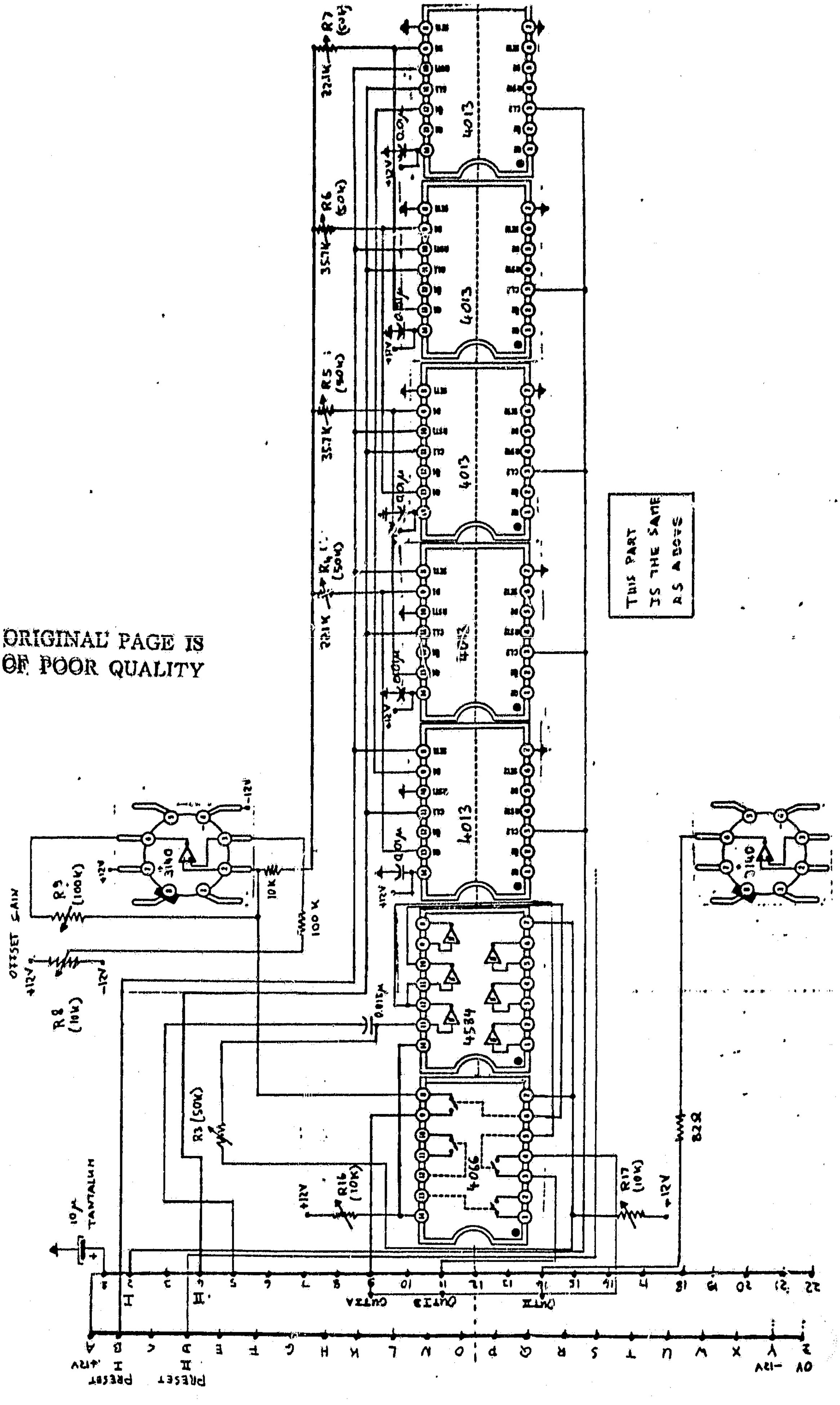

Figure 2.2. Sine Wave Generators with Amplifiers and Gates

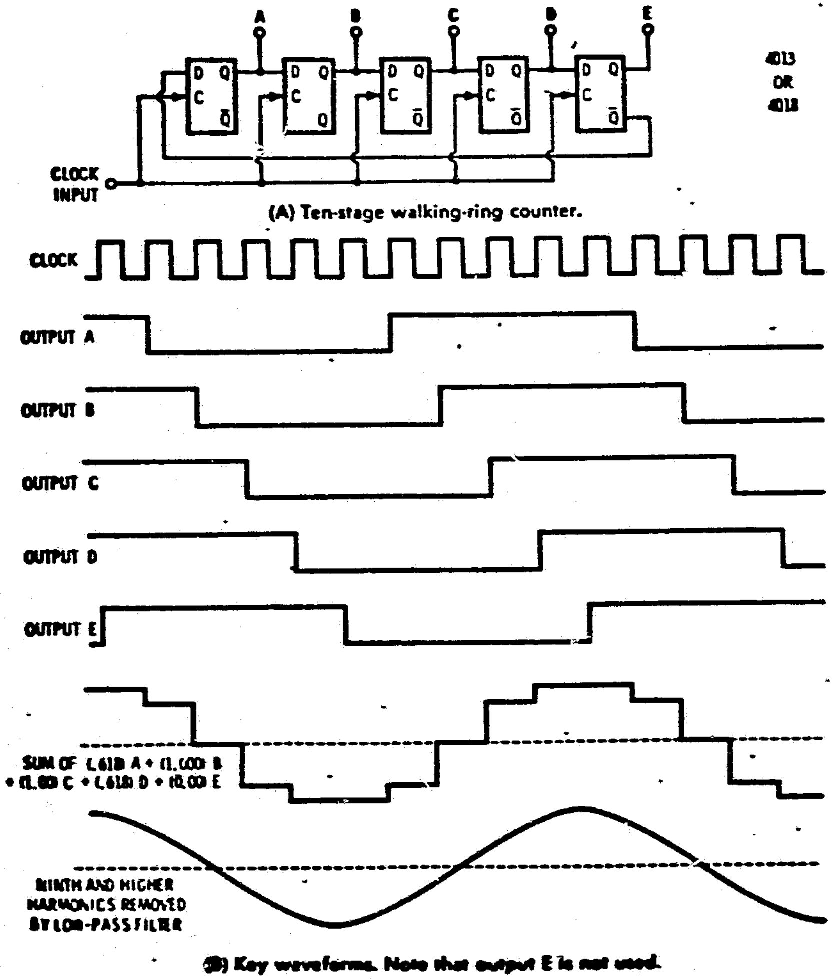

Figure 2.3a. Converting a Walking-ring Counter into a Digital Sine Wave Generator (CMOS Cookbook)

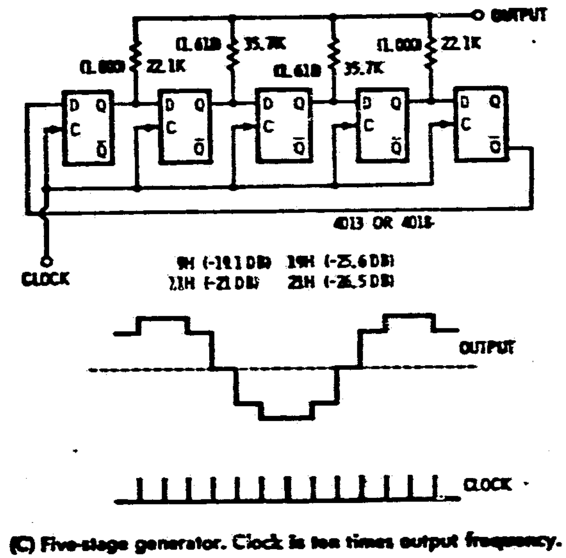

Figure 2.3b. Five-stage Generator (CMOS Cookbook)

the second generator.)

Two outputs of channel II are available: The SCHMITT TRIGGER 4584 and the ANALOG SWITCH 4066 connect the OUTPUT A with the amplifier output during the time interval $T = .8 \times .015 \times .10^{-6} \times R3$ second (R3 adjustable) and disconnect it from OUTPUT B as shown in Figure 2.4. Before and after T, OUTPUT B is connected to OUTPUT A but disconnected from the amplifier (important for receiving and amplifying the echo). PRESET I and II present the five FLIP-FLOP's such that each burst starts at 0 volts.

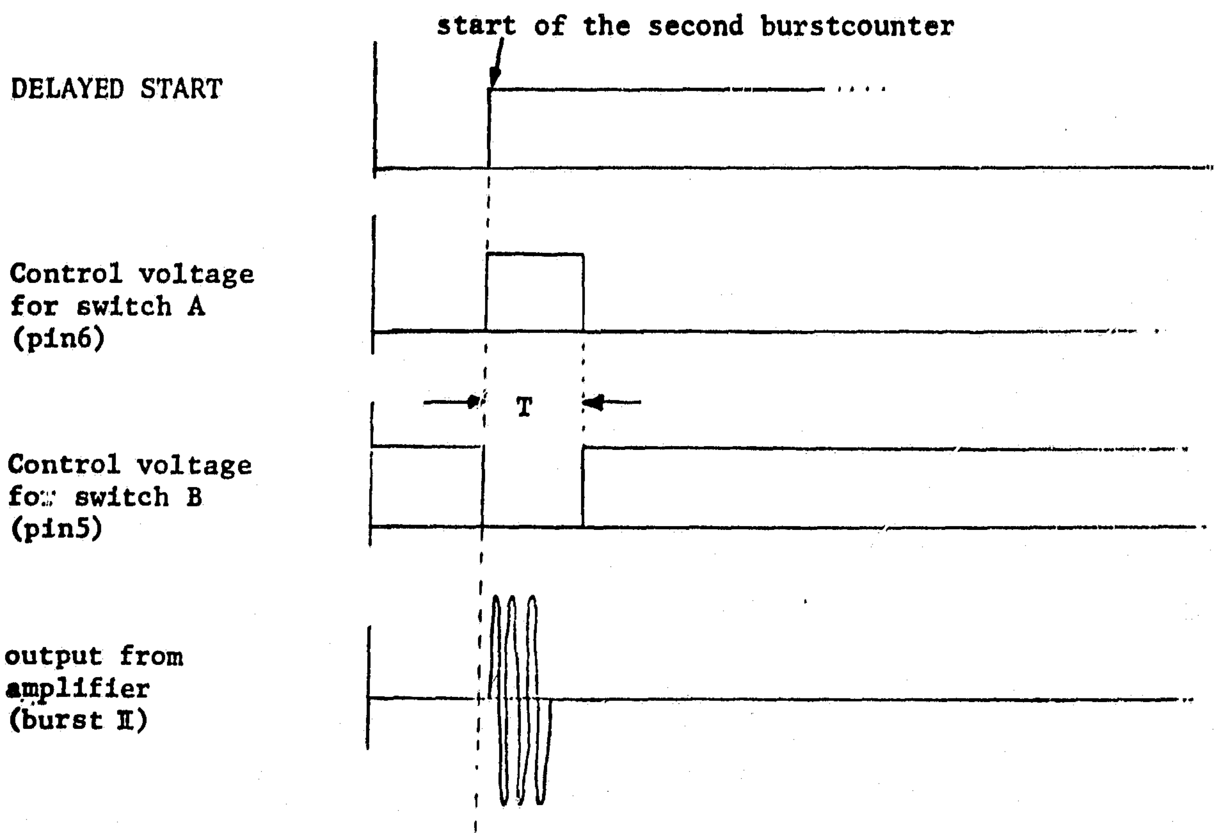

Figure 2.4. Pulse Diagram

The 10 μf tantulum electrolytic capacitor from point 1 to ground and the .01 μf disc capacitors from pin to 14 to ground (at the FLIP-FLOP's) stabilize the power supply and eliminate noise.[1]

2.3.3.2. The Burst Counters. The CMOS circuits used (see Figure 2.5) are:

-4017 DIVIDE BY 10 COUNTER WITH 1- OF -10 OUTPUTS

-4027 JK FLIP-FLOP

-4584 SCHMITT TRIGGER

-4081 2-INPUT AND GATE

The clock is divided by ten by one 4017. This new clock frequency goes to another 4017 whose 1- of -10 ouputs are connected to a 10 position switch on the panel. As soon as the chosen position of this switch and the HIGH output of the 4017 agree, the ENABLE goes to POSITIVE and the counter stops counting. Negative edge detectors (4584 with capacitors and resistors) generate set and reset pulses (spacing between these pulses is adjustable with R1/R2 on the panel) for the 4027, which produces a HIGH output for the time between the set and reset pulse. The 4081 finally allows the required number of clock pulses to pass (Figure 2.6).

2.3.3.3. The Delay Counter. The idea used (see Figures 2.7 and 2.8) to generate the delay is basically the same as

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[1]Don Lancaster, TTL Cookbook, Howard W. Sams Publication (1976).

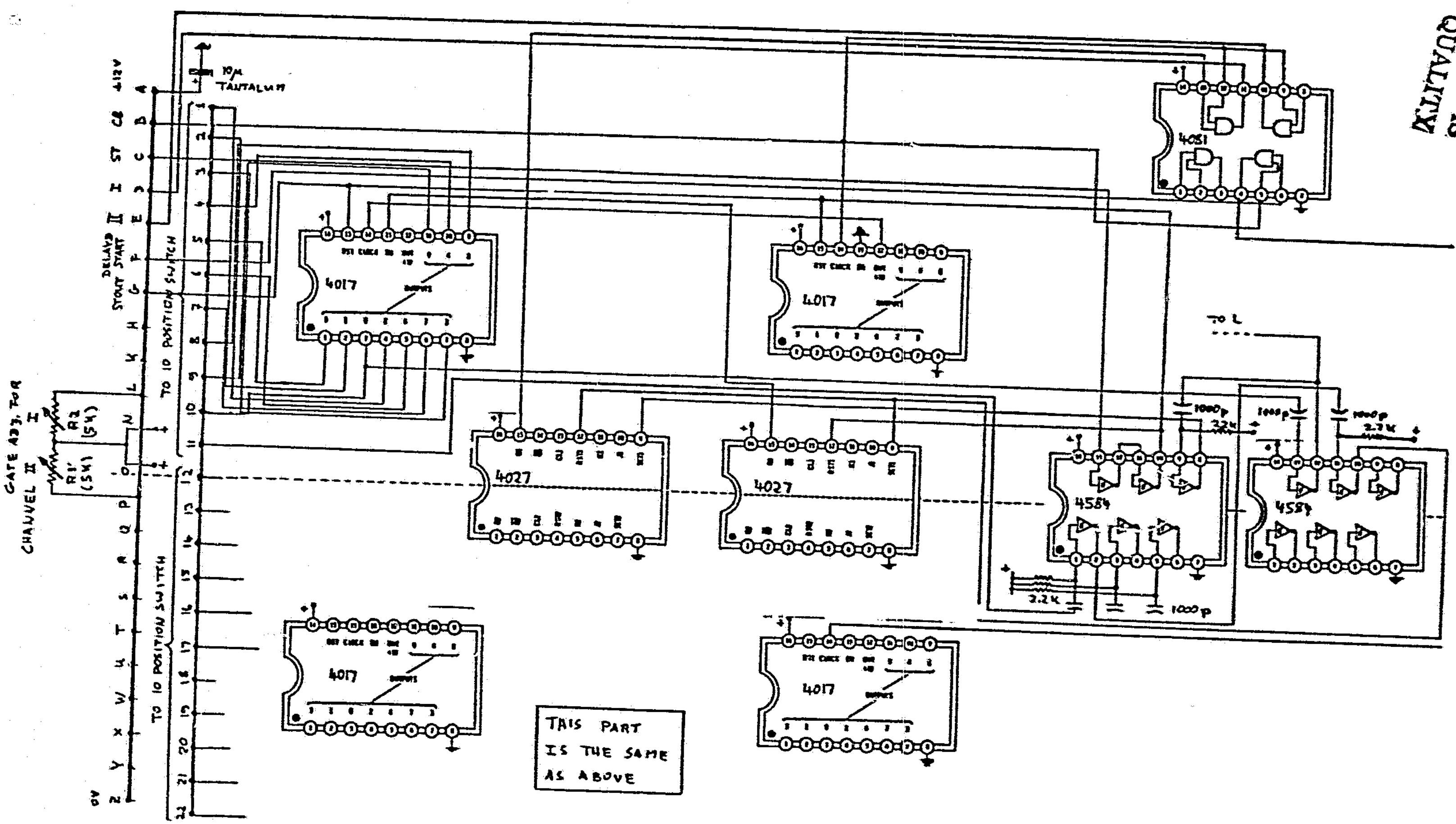

Figure 2.5. Burst Counters

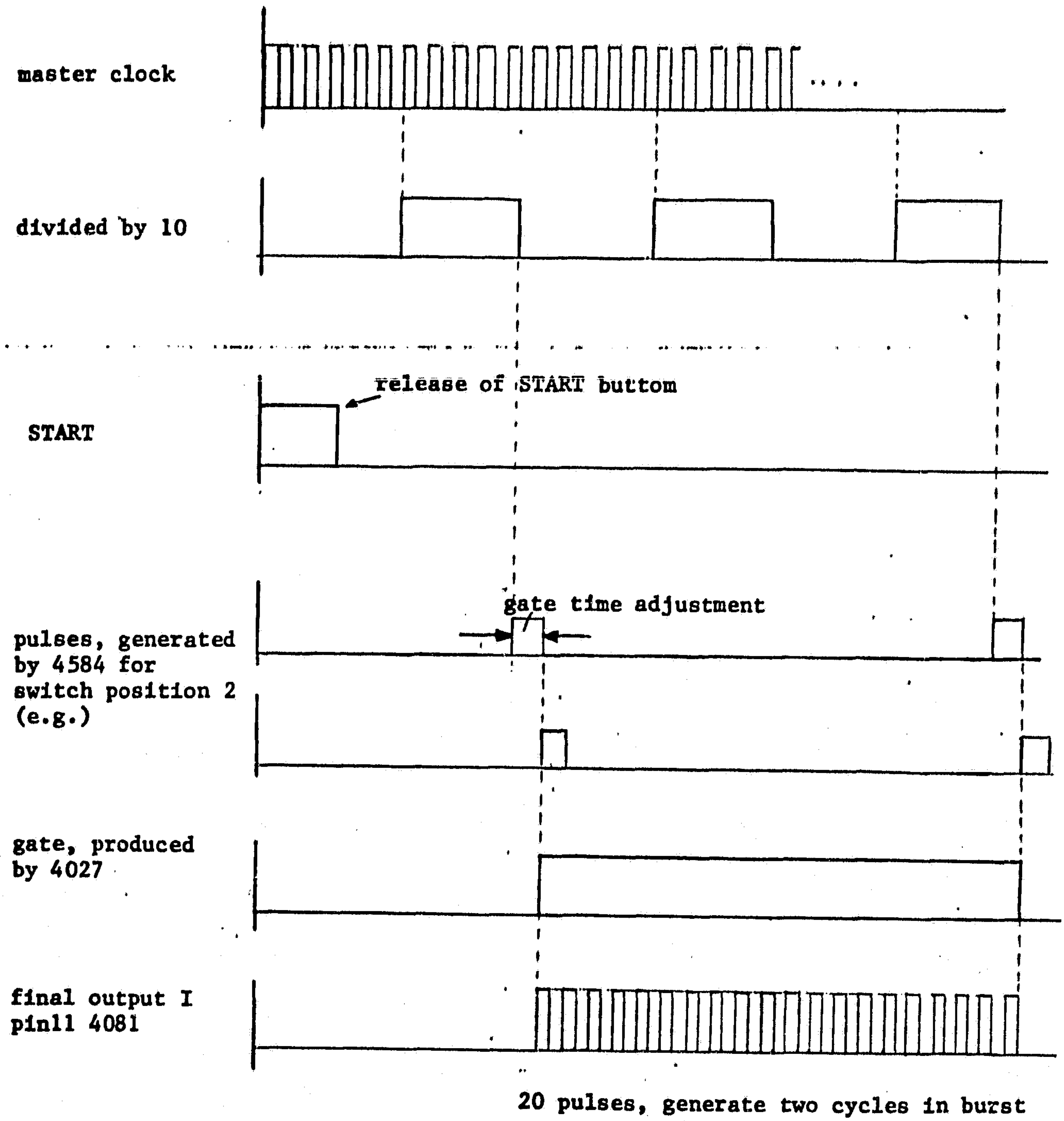

Figure 2.6. Pulse Diagram

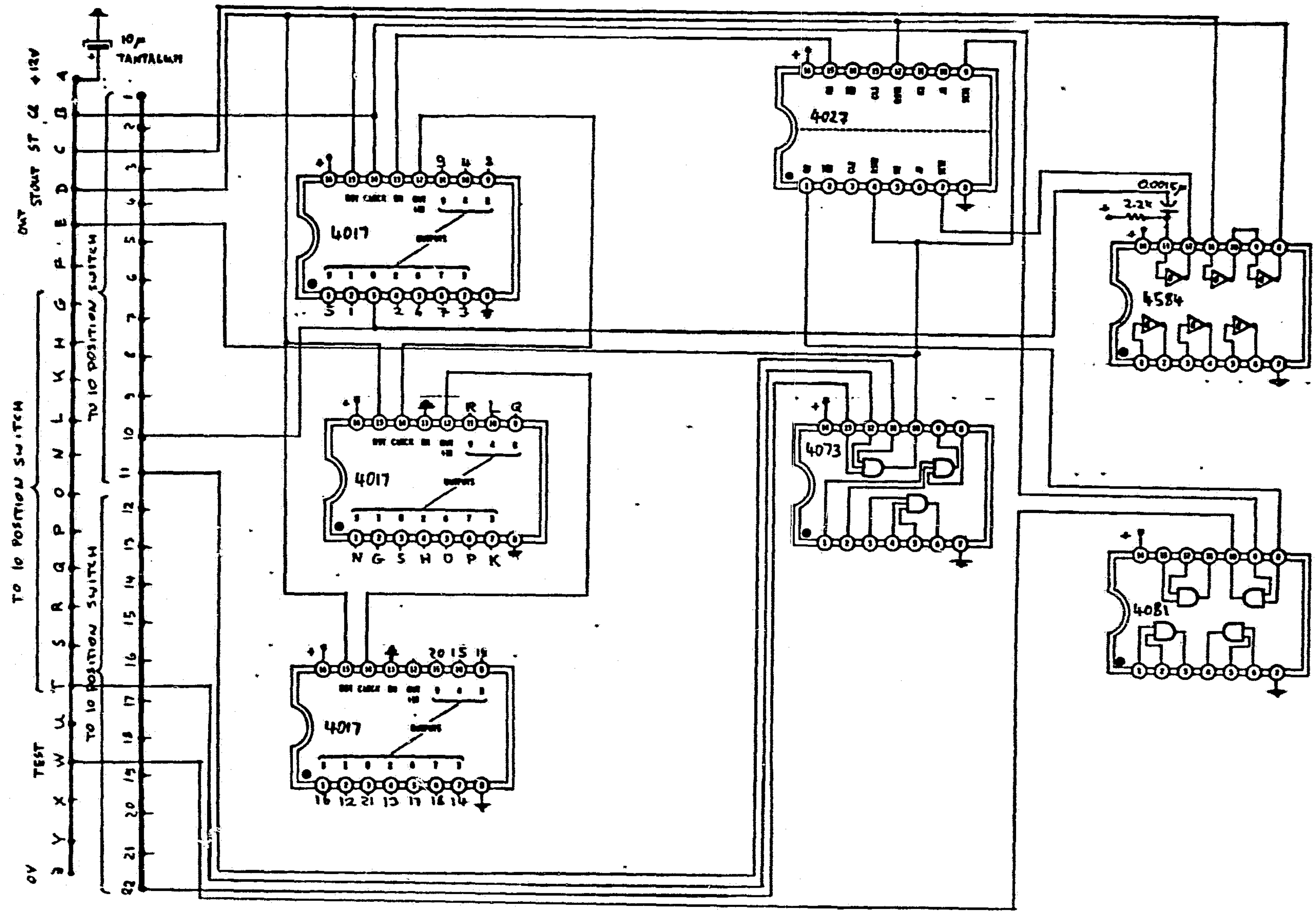

Figure 2.7. Delay Counter

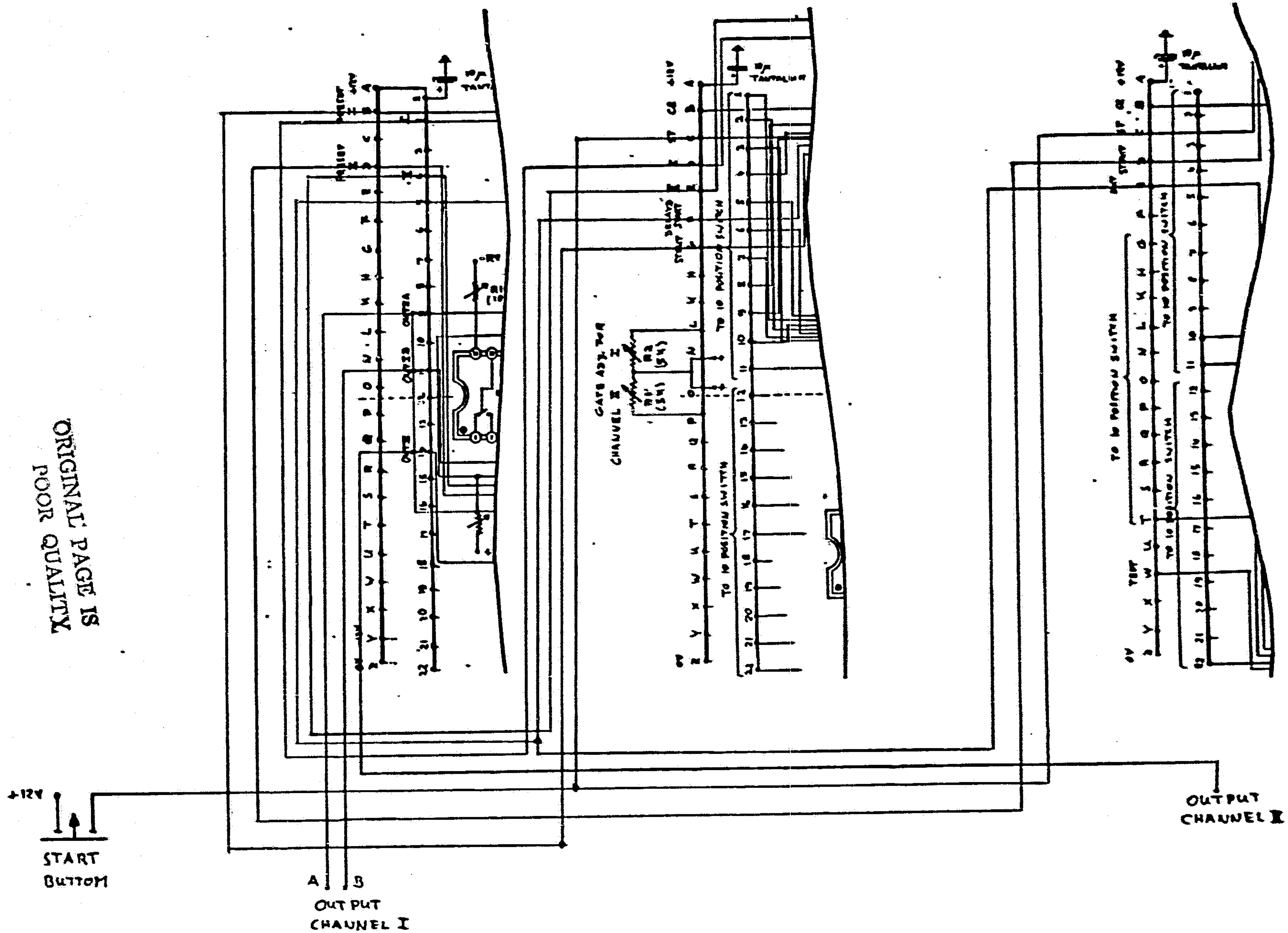

Figure 2.8. Connection of the Board

used for the burst counters. Three 4017's form a counter for three decades. The master clock frequency goes to the counter for the first decade, 1/10-th of this frequency to the second decade and 1/100 serves as clock for the third decade. As soon as the chosen positions of all three 10 position switches on the panel and on the three outputs of the 4017's agree, the 3-INPUT Gate 4073 yields a HIGH signal, which starts the second burst counter and enables the counter to continue counting. For testing purposes the output TEST yields the number of clock pulses, which generate the delay time, i.e., each pulse corresponds to 1/10-th of one sinusoid delay between burst I and burst II. The interconnections of the sections of the digital signal generator are shown in Figure 2.8.

2.4. Refinements of Output Capabilities

Several additions have been made to the basic design of the digital sine wave generator to make it compatible with the apparatus for the coal-slab thickness measurements. The primary refinement concerns provision of a large voltage, large impedance output to match the requirements of the transducer being used. The outputs from the sine wave generator come from CMOS operational amplifiers 3140 (see Figure 2.2) which are low output impedance devices with 10 V_{pp} output voltage. The Panasonic transducers used in the measurements require input voltage in the range 100 - 200 V_{pp} and present an essentially capacitive load. Two steps have been taken in an attempt to match these subsystems: Each output channel has been provided with an adjustable voltage divider, as shown in Figure 2.9, to provide adjustable output voltage between 0 and 10 V_{pp}. In addition, a buffer with step-up transformer designed and provided by MSFC engineers has been incorporated. A schematic of this device is shown in Figure 2.10. The measured characteristics of this amplifier are:

Gain	125:1
Maximum input voltage for distortion-free output	600 mV_{pp}
Frequency range	40 - 200 kHz

This device performs well with a resistive load. When connected to the transducer, however, a self-excited oscillation developed in the output section (transformer plus transducer). It is anticipated that this oscillation can be prevented by capacitive feedback through a capacitance of 1-4 pf.

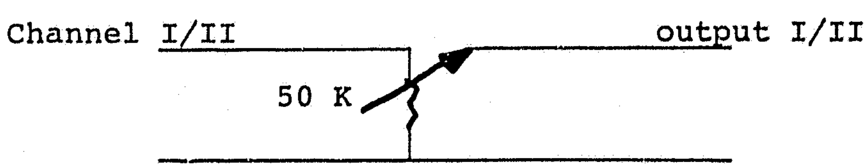

Figure 2.9. Schematic Diagram of Output Voltage Dividers.

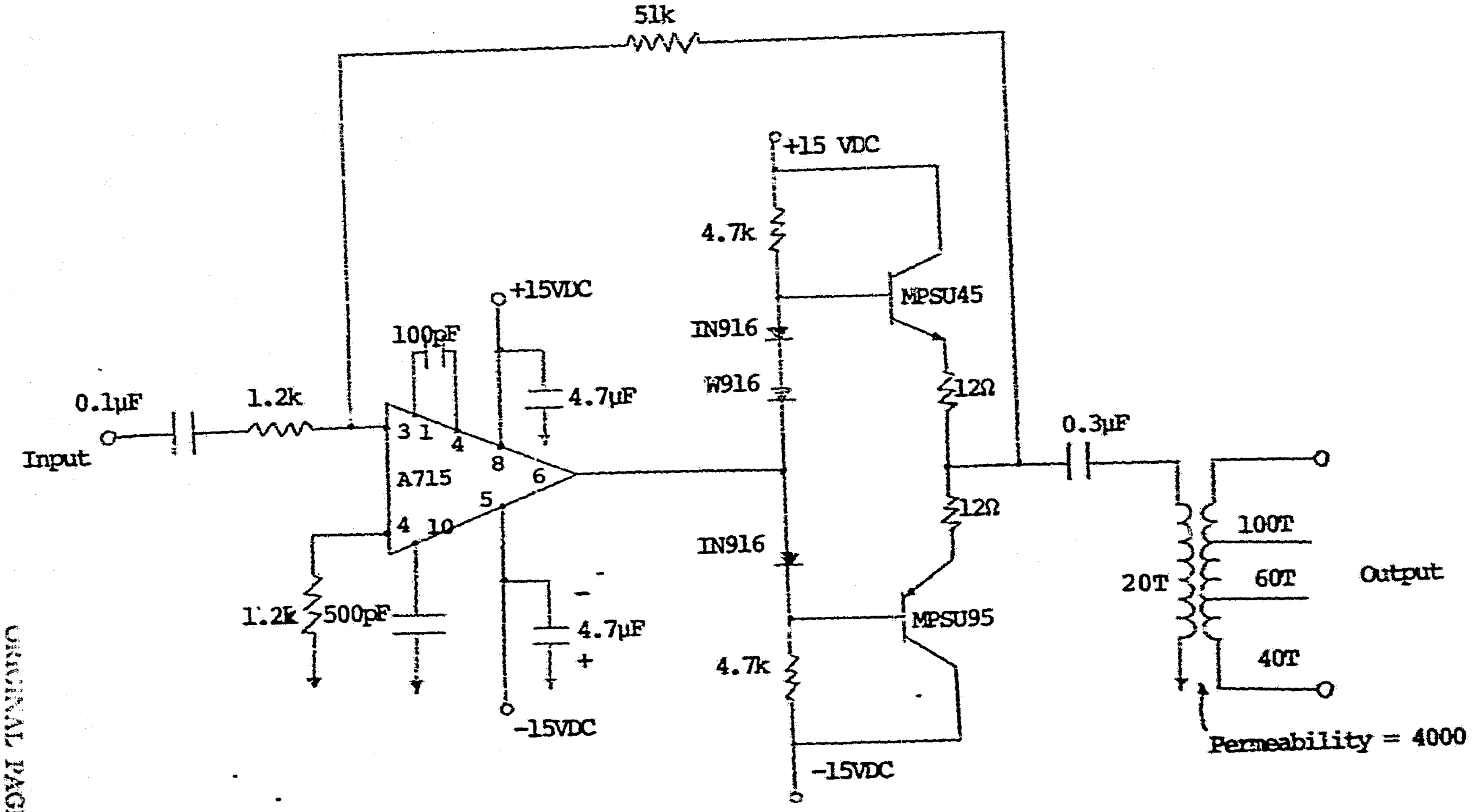

Figure 2.10. Schematic Diagram of Buffer Amplifier and Transformer.

The second refinement of the output from the digital sine wave generator is the provision of a TTL level trigger pulse to synchronize devices such as stepless gates. A 5V pulse with pulse width 3 μs can be generated[1] by detecting the negative edge at PIN START (identical with PIN PRESET on the generator board) as shown in Figures 2.11 and 2.12.

2.5. Testing and Performance

Figure 2.13 is a picture of the digital oscilloscope screen showing two cycles of a 10 kHz burst. At higher frequencies the noise content of the signal will increase by a small amount.

Figure 2.14 shows two bursts, the first with six cycles, the second (delayed) with four cycles. One can nearly cancel the two signals by superposing them in the correct manner.

Output W on the delay counter board yields the number of 1/10 cycles the second pulse is delayed. (Since there is no external adjustment similar to those at the burst counters, the chosen delay may deviate one or two 1/10 of a cycle from the actual delay if very small delays are selected.)

Figure 2.15 shows one burst and the reflected echoes received by a transducer after passing through a tank of water.

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[1]Don Lancaster, TTL Cookbook, Howard W. Sams Publication (1976).

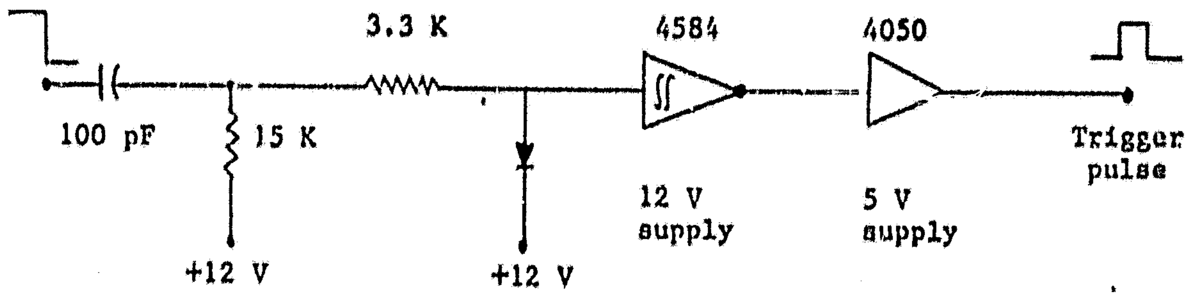

Figure 2.11. Stepless Gate.

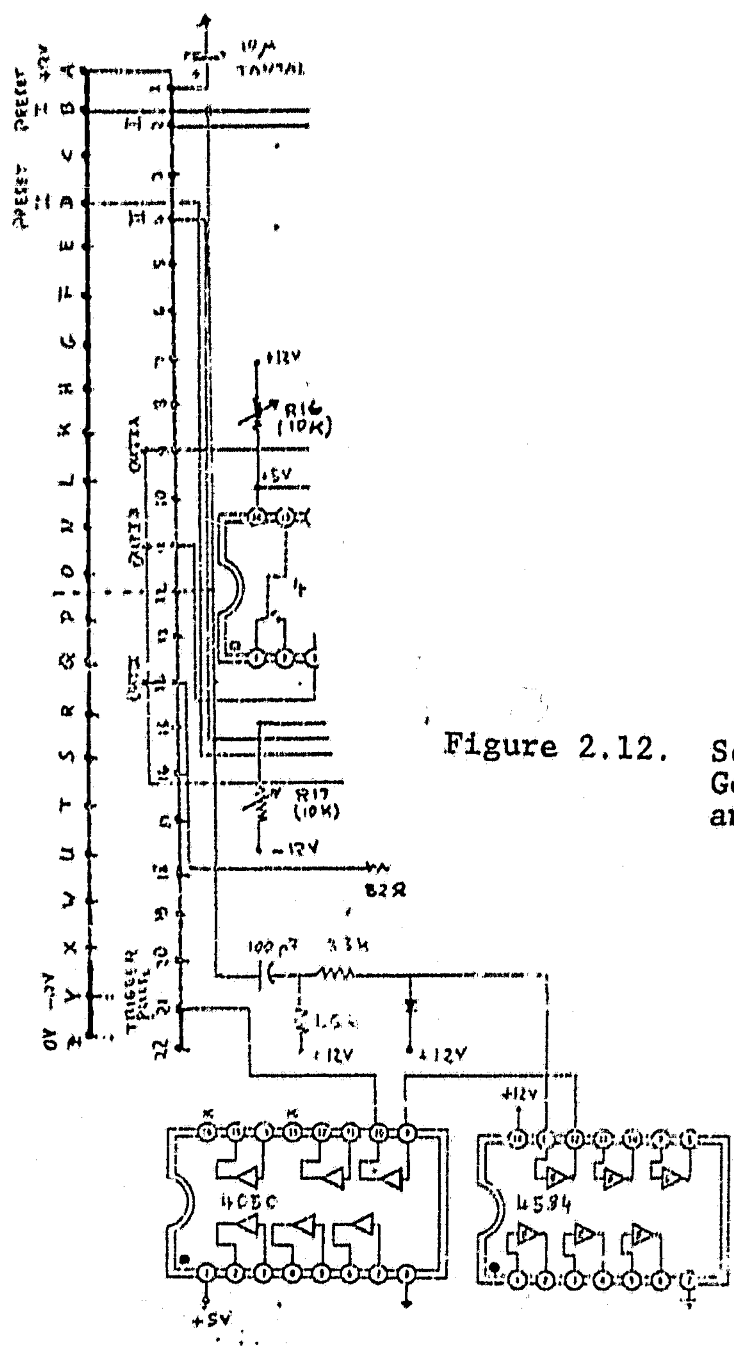

Figure 2.12. Schematic of Sine Wave Generators with Amplifiers and Gates.

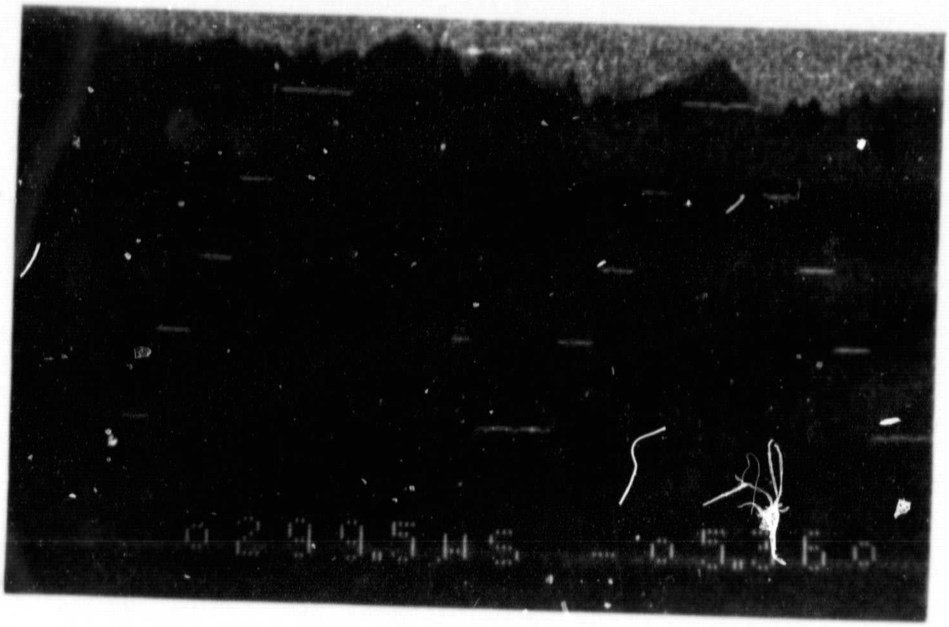

Figure 2.13. Two Cycles of a 10 kHz Burst

Figure 2.14. Two Bursts, the First with Six Cycles, the Second (delayed) with Four Cycles

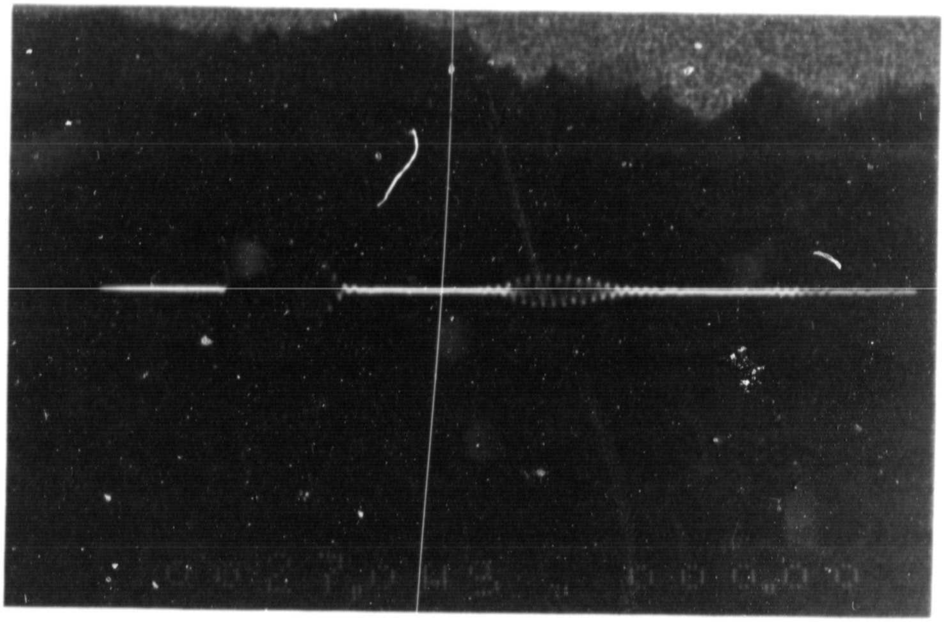

Figure 2.15. Transmitted Burst and Subsequent Echoes

Figures 2.16, 2.17 and 2.18 show the digital sine wave generator in the context of the complete experimental apparatus and top and front views of the generator.

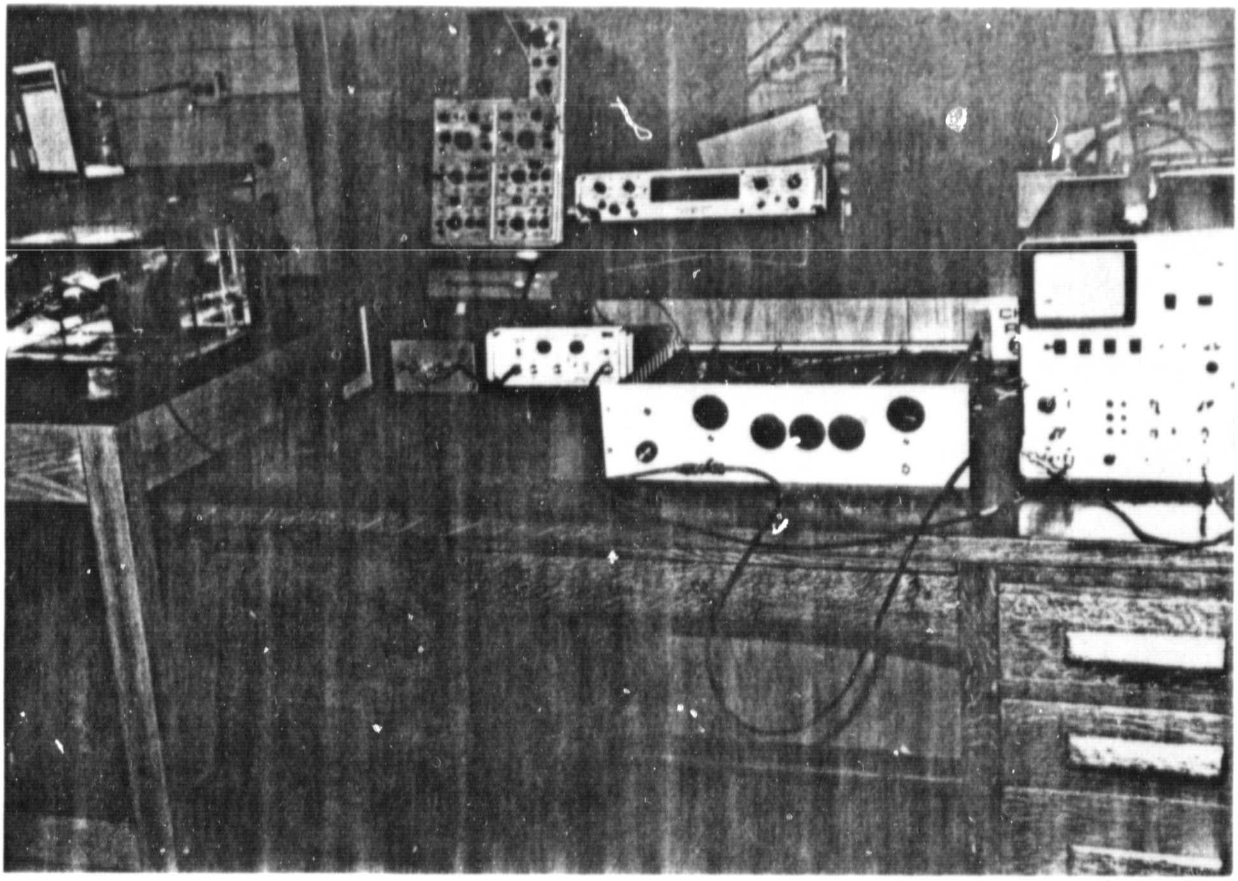

Figure 2.16. Layout of the Experimental System (Water Tank, Amplifier, Sine Wave Generator, Digital Oscilloscope).

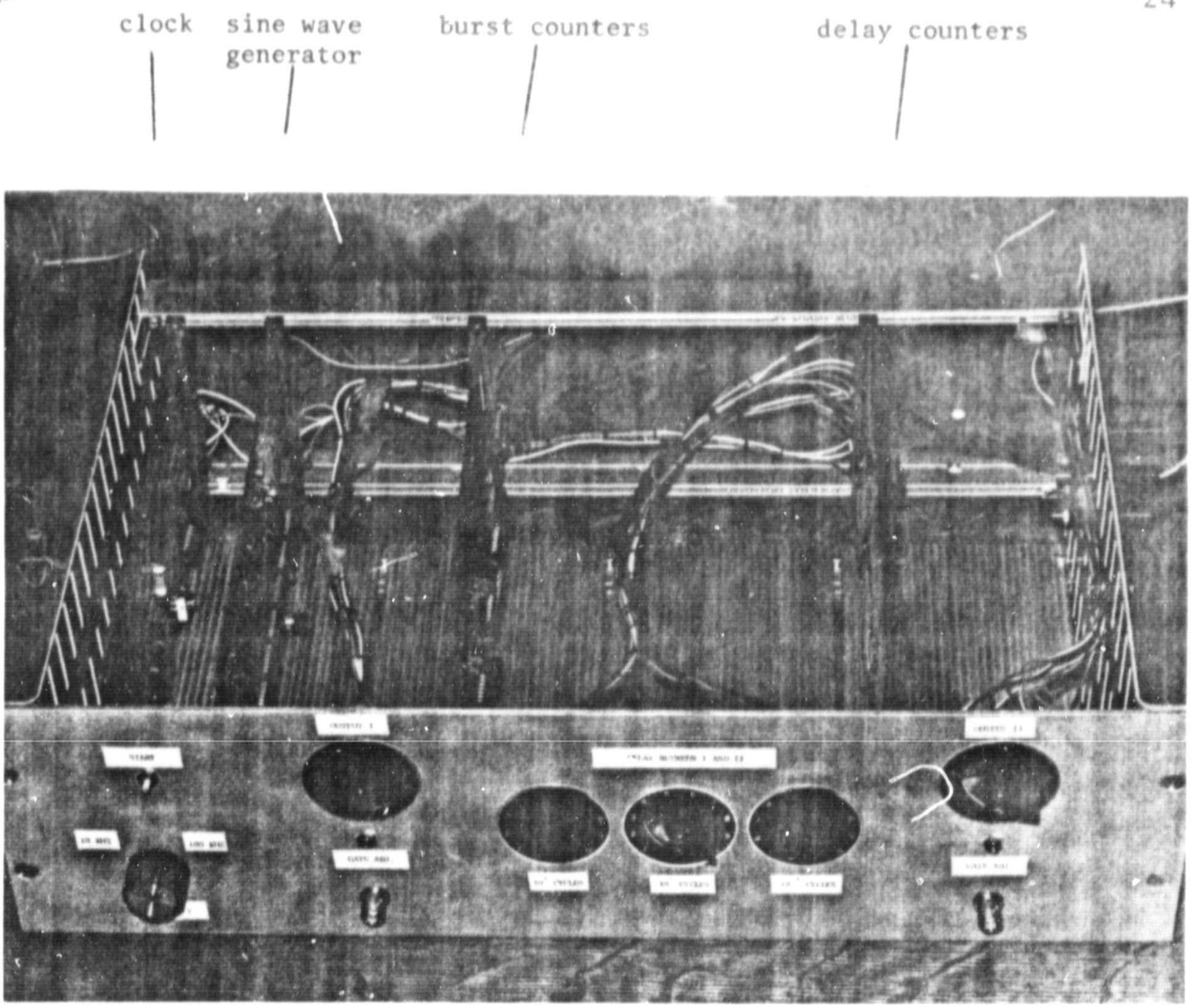

Figure 2.17. Top View of Digital Sine Wave Generator.

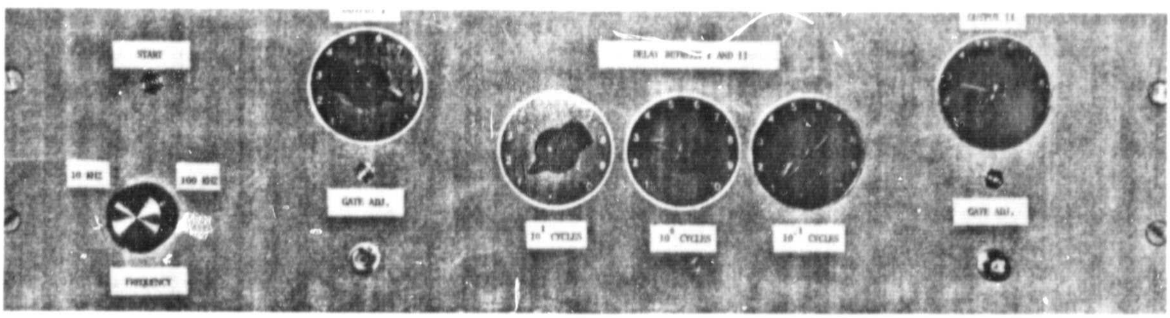

Figure 2.18. Panel (the Frequency will be Adjustable up to 500 kHz Later on).

Chapter III

PRELIMINARY MEASUREMENTS OF ACOUSTICAL PROPERTIES OF COAL

by Chew, C.-H., A. D. Pierce, and W. J. Hadden, Jr.

3.1. Abstract

A series of experiments were carried out to obtain some values for the sound speed and attenuation coefficient of coal. The experiments were carried out with apparatus developed in a project directed toward development of a method to determine coal slab thicknesses using ultrasound. The theoretical derivations are based on the acoustic principles of wave reflection and transmission at an interface between two media. The results, when compared to those published in recent literature, verify the applicability of the theory and of the experimental apparatus.

3.2. Introduction

A survey of recent literature reveals sizeable discrepancies in quoted values for the wave speed in coal. Some of the reported values are:

D. P. Shumskii[1] - hard layer - 1180-1250 m/sec

J. R. Hearst, et al.[2] - compressional velocity

borehole logs - 2050-2150 m/sec

lab sample - 2300 m/sec

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[1]D. P. Shumskii, "Ultrasonic Method of Estimating the Structure and Fissuring of Coals," Soviet Mining Science 11 (March - April 1975), 147-149.

[2]J. R. Hearst, et al., "Fractures Induced by a Constrained Explosion in Kemmerer Coal," Int. J. Rock Mech., Min. Sci. and Geomech., Abstr., 13 (1976), 37-44.

B. M. Butcher and A. L. Stevens[1] - McKinley Mine, Window Rock, Arizona

longitudinal wave speed - 2330 m/sec

elastic wave velocity - 2280 m/sec

Negligible data exist on the value of the attenuation coefficient in coal.

The measurements described here were obtained via an extremely simple experimental procedure: comparison of travel times for an acoustic pulse over a fixed distance with the intervening medium consisting of: i) a water buffer (the control) and ii) the water buffer plus a slab of coal. The primary limitations on the accuracy of these measurements are the accuracies with which the complete path length and the coal slab thicknesses are known.

3.3. Theoretical Basis of Experiments

To determine some values for the phase velocity and attenuation coefficient for sound in coal and to test the experimental apparatus, a series of simple experiments were performed. Elementary acoustic theory for the reflection and transmission of sound from the interface between the two media were used to solve for these parameters.[2]

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[1] B. M. Butcher and A. L. Stevens, "Shock Wave Response of Window Rock Coal," Int. J. Rock Mech., Min. Sci. and Geomech., Abstr., 12 (1975), 147-155.

[2] Allen D. Pierce, Acoustics - An Introduction to Its Physical Principles and Applications. Draft of manuscript to be published by McGraw-Hill Book Company (1981) Chapter 3.

3.3.1. Phase Velocity of Sound in Coal

The sound speed in coal was determined by measuring the travel time of ultrasonic pulses from the source transducer to the receiver transducer with and without the coal sample inserted in the water buffer material. This set-up is shown in Figure 3.1. The phase velocity is determined from the equation shown in that figure.

3.3.2. Attenuation Coefficient for Sound in Coal

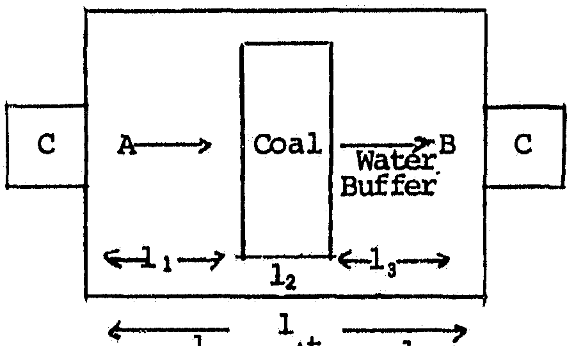
For the determination of the attenuation coefficient, we consider the configuration shown in Figure 3.2. Ensuring continuity of pressure and velocity at each coal-water interface leads to the following relationship between the transmission coefficient, T, and the acoustical properties of coal and water:

$$\exp(2\alpha\ell) = [4/T^2 + 2(K^2 - 1)\cos(2k_r\ell) - 4K\sin\delta\ \sin(2k_r\ell) - \exp(-2\alpha\ell)(1 - 2K\cos\delta + K^2)](1 + 2K\cos\delta + K^2)^{-1}$$

Here K and δ are defined by:

$$K\,e^{i\delta} = 1/2\left(\frac{Z_c}{Z_\omega} + \frac{Z_\omega}{Z_c}\right)$$

with Z_ω the characteristic impedance for water and Z_c



$$\frac{1}{V_c} = \frac{\Delta t}{l_2} + \frac{1}{V_w}$$

A - Incident Wave
B - Transmitted Wave
C - Transducer
V_c - Speed of Sound in Coal
V_w - Speed of Sound in Water
Δt - Difference in Travel Times With and Without Coal Sample
l_2 - Thickness of Coal Sample

Figure 3.1. Determination of Sound Speed.

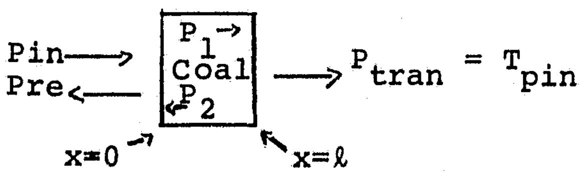


Figure 3.2. Determination of Reflection and Transmission Coefficients.

given by $\omega\rho_c/k_c$. The notation $k_c = \omega/V_c$ is employed in Equation (1).

3.4. Apparatus

The layout of the experimental apparatus used to obtain the desired data is shown in Figure 3.3. The equipment used was a water tank including supporting structures for the transducers and coal, two matched ultrasonic transducers, a digital sine wave generator, an amplifier, and a digital oscilloscope. The transducers were Panametrics Model V 3033 matched transducers whose operating frequency is .5 MHz. The water tank was constructed of plexiglass and fitted with aluminum cylinders for housing the transducers and an aluminum plate for holding the coal sample. The aluminum plate extends across the width of the tank to prevent spurious diffraction effects in the received signals. The digital sine wave generator is a device capable of producing sinusoidal bursts of fixed frequency generated by CMOS walking ring circuits. The digitally generated bursts are characterized by controllable phase, a frequency spectrum that is quite narrow, exactly determined beginning and end, and controllable length.

3.5. Data Collection and Analysis

In implementing equation (1) for the attenuation coefficient, α, we initially choose $\delta = 0$ and neglect the term involving $\exp(-2\alpha\ell)$. Thus we can obtain an initial

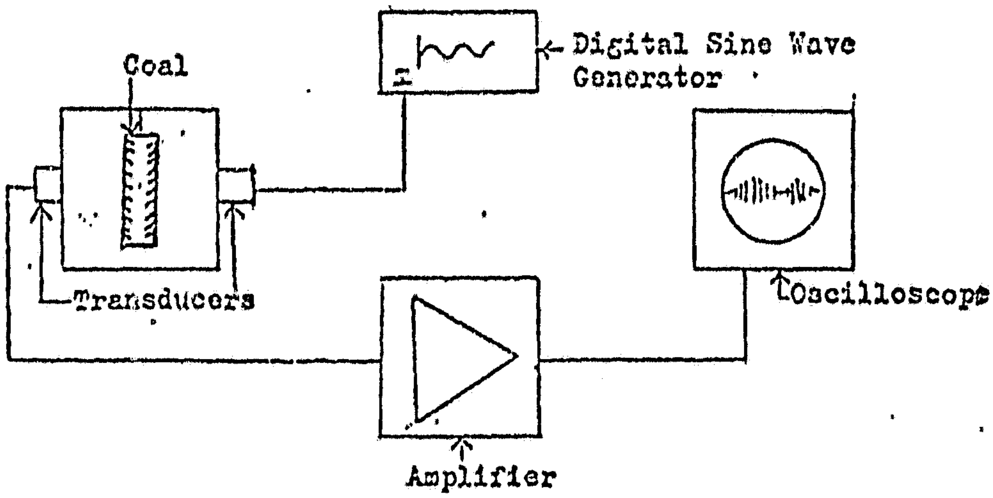


Figure 3.3. Layout of Experimental Apparatus.

approximation for the attenuation coefficient α which is used in the definition of Z_c to yield new values for K and δ in Equation (2). These manipulations are extended to an iterative procedure which is implemented by a computer program. The resulting values of sound speed and attenuation factor are presented in Table 3.1.

3.6. Results and Conclusions

The values for the sound speed in coal shown in Table 3.1 are in reasonably good agreement with previously published values.[1,2] The values for the attenuation constant agree reasonably well with those reported to us informally by NASA MSFC personnel. (We believe the values for the 1.96 cm. slab to be spurious.) In view of the relatively crude measurement procedure this agreement is encouraging.

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[1] J. R. Hearst,, et al., "Fractures Induced by a Constrained Explosion in Kemmerer Coal," Int. J. Rock Mech., Min. Sci. and Geomech., Abstr., 13 (1976), 37-44.

[2] B. M. Butcher and A. L. Stevens, "Shock Wave Response of Window Rock Coal," Ibid., 12 (1975), 147-155.

Table 3.1. Phase Velocity and Attenuation Constant for Coal Measured by Substitution Method.

Sample Thickness (cm)	Speed of Sound (m/sec)	Peak to Peak Voltage Without Sample (mV)	Peak to Peak Voltage with Sample (mV)	Voltage Ratio	Total Time Immersed in Water (min)	α Nepers/cm	$\alpha\lambda$ Nepers
1.38	2510	952	219	4.35	20	0.97	2.44
1.51	2490	928	149	6.24	20	1.13	2.8
1.63	2440	920	106	8.65	20	1.24	3.04
1.96	2550	968	227.2	4.26	20	0.662	1.69
2.52	2420	960	72.8	13.19	20	0.97	2.44

One feature of the present investigations that may prove to be of further interest was the variability of the results with (presumably) the water content of the coal. During exploratory tests, the amplitude of the signal received and its time of reception varied appreciably for immersion times varying from zero to twenty minutes. For the tests reported in Table 3.1, the samples were soaked for at least 20 minutes, or until the transit times and received amplitudes stabilized.

Chapter IV

THEORETICAL BACKGROUND FOR ECHO-CANCELLATION EXPERIMENTS

by Chew, C.-H and A. D. Pierce

Because of the excellent signal controlling capabilities of the digital burst generator, the investigators chose an echo-cancellation method for further exploration of the acoustic properties of coal. The particular technique chosen is an adaptation for the digital generator of a method used originally by McSkimin.[1] Numerical simulations of the analysis for expected data have been performed in order to provide a framework for data reduction.

The echo-cancellation method involves sending sinusoidal pulses at a sample of coal from diametrically opposed directions as illustrated schematically in Figure 4.1. The essence of the method consists of adjusting the voltage applied to, for example, the transducer at the right in Figure 4.1, and the time at which this transducer is excited so that the transmitted pulse incident on the transducer at the left cancels the pulse from the left transducer reflected from the face of the sample back to the same transducer. The representations for the waves incident from the left and right transducers are shown in Figure 4.1, as is the expression for the sum of the reflected and transmitted waves incident on the left transducers.

[1]H. J. McSkimin, "A Method for Determining the Propagation Constants of Plastics at Ultrasonic Frequencies," J. Acoust. Soc. Am. 23 (1951), 429-434.

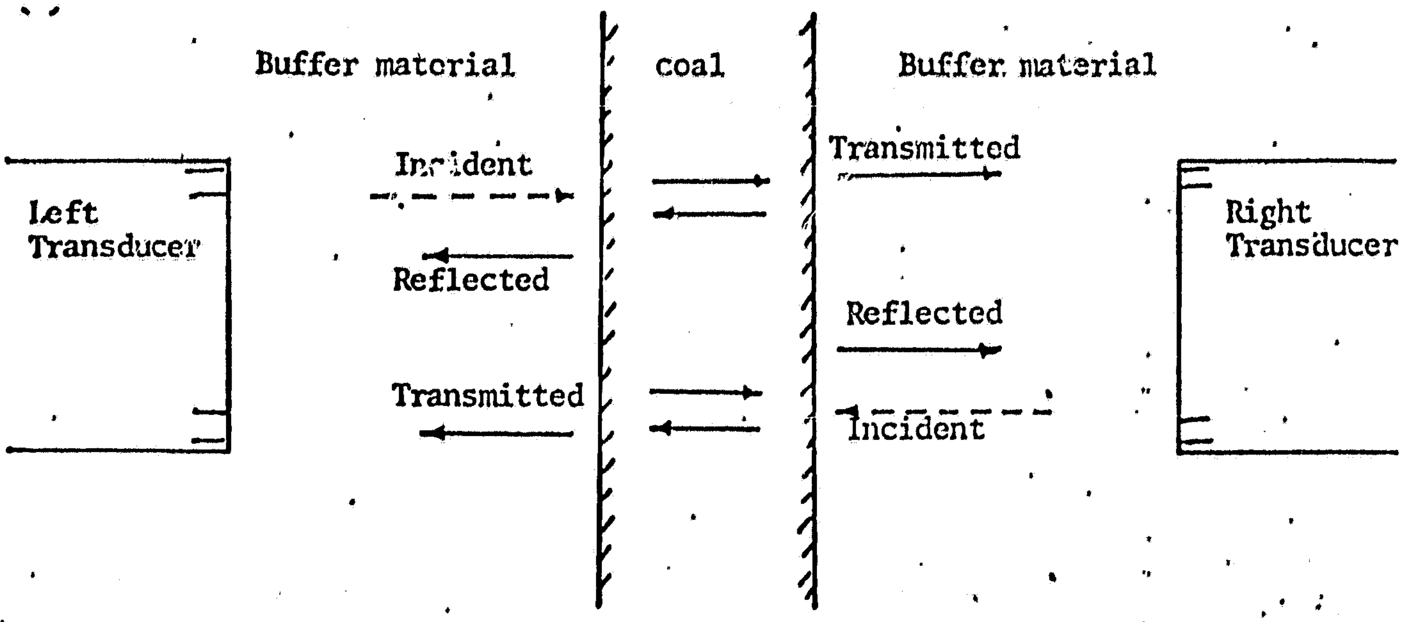

Figure 4.1. Experimental configuration for echo-cancellation method. The incident waves from left and right are expressed as $P_{in,L} = A \exp i(kx - wt)$ and $P_{in,R} = B \exp i(ky - wt)$, respectively. The pressure received at the left transducer is $P_{ref,L} + P_{tr,R} = R_{Pin,L} + T_{Pin,R}$.

The reflection coefficient, R, and transmission coefficient, T, in this case are:

$$R = \frac{i(Z_c/Z_w - Z_w/Z_c)\sin k_c l}{2(\cos k_c l - iK \sin k_c l)} \qquad (1)$$

and

$$T = \frac{1}{\cos k_c l - iK \sin k_c l} \qquad (2)$$

where Z_w is the characteristic impedance of water, Z_c is the sum quantity for coal ($=i\omega\rho/k_c$), k_c is the complex wave number in coal ($=\omega/V + i\alpha$) and the quantity K is $1/2(Z_c/Z_w + Z_w/Z_c)$.

Assuming that the amplitude of the pulsed wave is proportional to the voltage applied to the transducer, the relation between the complex wave amplitudes for cancellation between the transmitted and reflected pulses can be expressed in terms of the relative gain G for the transducer voltages and the phase shift ϕ between these voltages by

$$(B/A)_{null} = Ge^{-i\phi} = -R/T \qquad (3)$$

which, when Equations (1) and (2) are employed, allows the determination of the sound speed V_c and attenuation factor α from G and ϕ.

After considerable manipulation, Equation (3) can be recast by equating the magnitudes and phases of both sides as two coupled transcendental equations with

$$\theta = \omega \ell / V_c, \quad x = \alpha V_c / \omega \ell, \quad \text{and} \quad X = Z_w / P_c \omega \ell .$$

$$\tan\theta = \text{tank}\,(x\theta)\,\tan\left[\phi + \tan^{-1}\left\{\frac{x[\theta^2(1+y) = X^2]}{\theta^2(1+y) - X^2}\right\}\right] \tag{4}$$

and

$$4\theta^2(1+y)G^2 = X^2[\sin^2\theta + \sinh^2(x\theta)][X^{-4}\theta^4(1+y)$$

$$- 2X^{-2}\theta^2(1-y) + 1] \tag{5}$$

Two approaches have been used in obtaining solutions of these equations with representative values for the parameters specified. In the first, the gain G, computed from Equation (5), is plotted as a function of $\alpha 1 (=x\theta)$ for a range of values of x as shown in Figure 4.2. Similarly, the phase shift ϕ computed from Equation (4) is plotted versus θ, as shown in Figure 4.3. For given data, G and ϕ, the sound speed and attenuation factor are determined by finding the values of θ and α (and the associated value of their ratio x) for which the points on the $G_x - \alpha$ curve and the $\phi_x - \theta$ curve imply consistent values. This procedure can be carried out graphically by assuming a value for the x and determining θ for the given ϕ from Figure 4.3 and α for the given G from

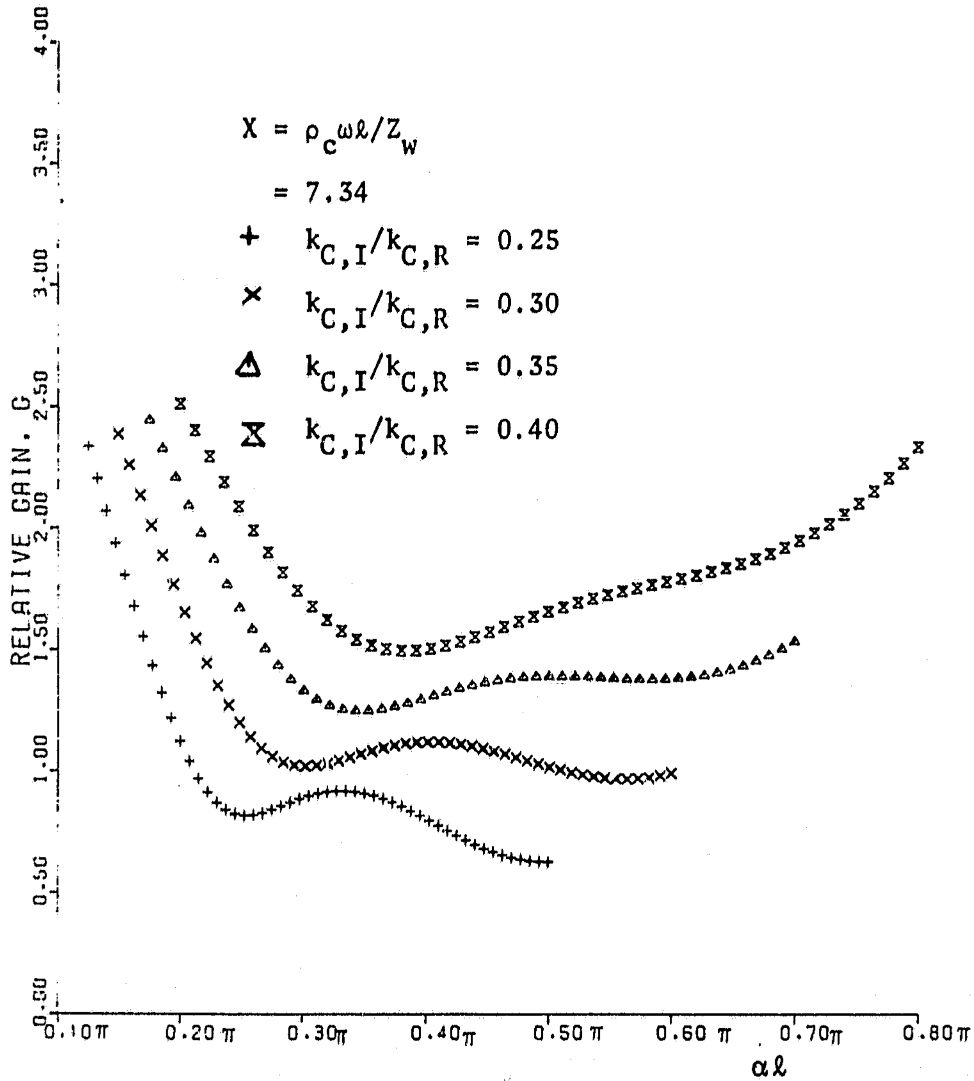

Figure 4.2. Plot of the Relative Gain, G, versus $\alpha\ell$ for Fixed X = 7.34, and Various Other Ratios of $k_{C,I}/k_{C,R}$ = x.

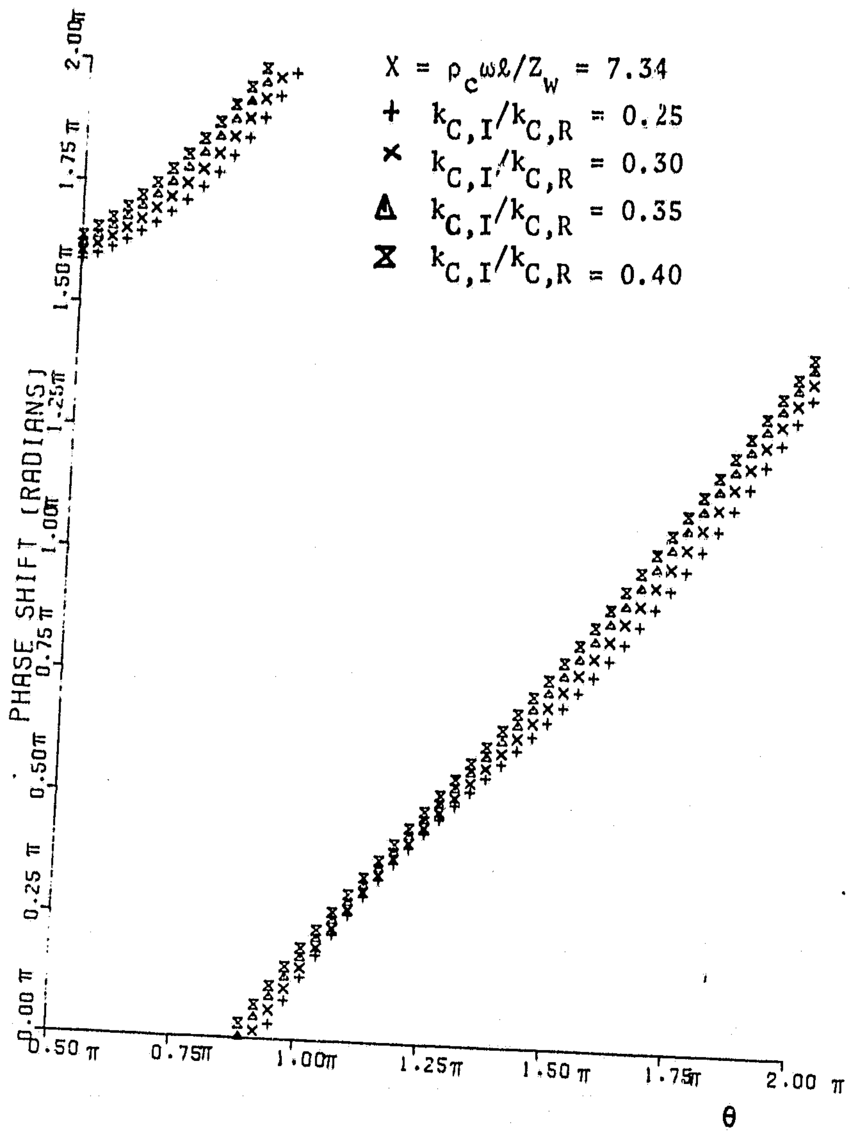

Figure 4.3. Plot of the Phase Angle, θ (radians) versus $\alpha\ell$ for Fixed X = 7.34, and Various Ratios of $k_{C,I}/k_{C,R}$ = x.

Figure 4.2. If α is not the same as $x\theta$, a new value for x is determined from the values of α and θ, and the process is repeated until consistency is obtained.

Although the above procedure can be made to work by manual searching, it is cumbersome and difficult to convert for solution by computer. (This procedure was, in fact, based on forms of Equations (4) and (5) in which the data G and ϕ were expressed as functions of the other variables.) As an alternative, Equations (4) and (5) were obtained so as to facilitate iterative solution for θ and x, using a program written for a hand-held calculator (specifically, the Texas Instruments SR-58.) In this approach, an initial value for x is assumed and equation (4) is solved by interation as

$$\theta_{n+1} = \tan^{-1} (\text{r. h. s. of Equation (4) with } \theta = \theta_n) \quad (6)$$

Convergence is quite rapid and is relatively insensitive to x. This value of θ is then used in a second subprogram in which Equation (5) is solved iteratively for $y = (x^2)$. Convergence is somewhat slower in this case. The final value of x is then used in the calculation of a new value of θ which is compared with the previous value. The process is repeated until satisfactory agreement is reached. Finally, the sound speed V_c and attenuation factor α are determined from the definitions of θ and x [preceding Equation (4)]. The results of sample calculations, using typical parameter values, are presented in Figure 4.4. As indicated by the format of these figures, repeated computations based on Equation (4) are most efficiently performed by choosing successive values of the phase shift, ϕ, and finding the values of θ and x, which are consistent with various values of the gain factor G. Computations following this algorithm indicate that the results are periodic in ϕ, with period π.

It can also be seen that this procedure allows rapid determination of the wave speed (from $\theta = W\ell/V_c$) and attenuation factor α for given G and ϕ from experiments.

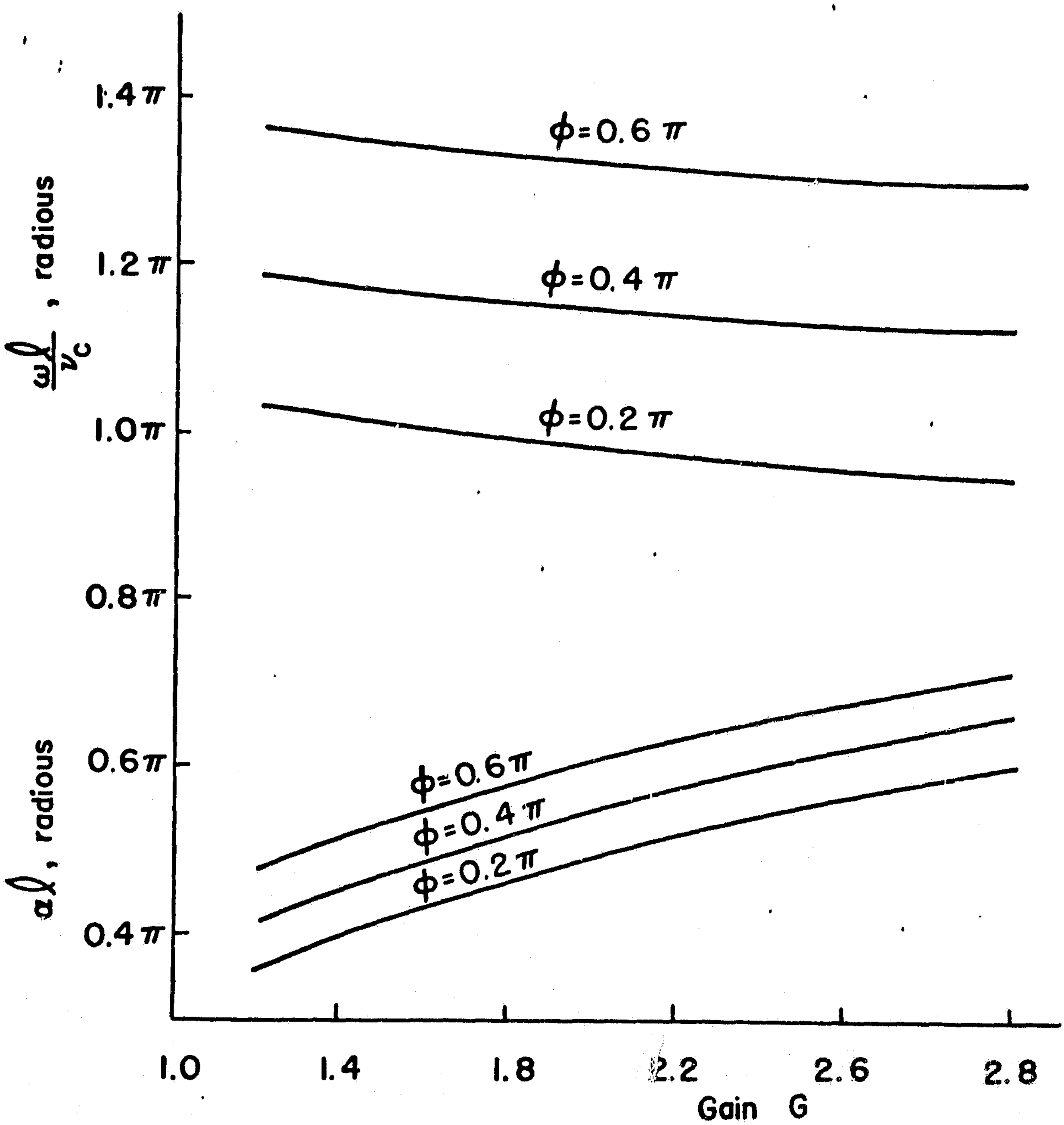

Figure 4.4. Determination of ν_c and α from G and ϕ.

Chapter V

THEORETICAL MODELS OF WAVE PROPAGATION IN COAL

by Chew, Chye-Heng

5.1. Introduction

In view of the lack of experimental evidence concerning the sound velocity and attenuation constant for coal, it is extremely desirable to develop a theoretical model of coal as a substance which supports wave propagation, in order that variations of the acoustical properties of coal with frequency and with important physical parameters can be studied via numerical simulations of wave propagation. The results of such studies will facilitate the choice of frequency ranges for coal-slab soundings. The primary goals in choosing a theoretical model are: 1) prediction of acoustical properties consistent with existing experimental data; 2) necessity for only a small set of physical parameters for prediction of acoustical quantities; and, 3) close correlation of physical parameters with those presently used for classification of coals.

This chapter describes several models which were chosen for investigation because of certain characteristics which were thought to be similar to those of coal. Two models have been studied rather thoroughly. The first, based on wave propagation in a porous elastic medium, has been rejected as inconsistent with experimental data, as explained below. The second model, based on dislocation theory, has yielded more encouraging results. Additional models are being investigated, as indicated at the end of the chapter.

5.2. Porous Viscoelastic Material

Due to the porous nature of coal, it was first thought that the viscous loss due to fluid flow through the pores may contribute significantly to the attenuation of wave propagation through coal. Assuming that the mechanisms of attenuation are additive, we will proceed to determine the contribution of the viscous effect to the attenuation.

As discussed in Sec. 5.4, the attenuation in coal due to viscous effect is too small (attenuation = $2.5 \times 10^{-4} m^{-1}$) to have any significant contribution.

5.3. Theory of Dislocations to Explain the Attenuation in Coal

From the creep experiment performed by Pompery,[1] the creep viscosity of coal was given as 4.8×10^{16} poises. This shows that coal is better modelled as a solid than a polymer solid.

Knopoff[2] found that for earth materials, the internal friction Q^{-1} is almost independent of frequency in the low

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[1] C. D. Pompery, "Creep in Coal at Room Temperature," Nature 176 (1956), 279-280.

[2] L. Knopoff, "Attenuation of Elastic Waves in the Earth," Chapter 7 in Physical Acoustics, Principles and Methods, Vol. 3B, edited by W. P. Mason and R. N. Thurston, Academic Press, New York (1965), 287-322.

kilohertz range. Mason[1] found that the internal friction for the earth materials obtained by Knopoff, and the fine-grained Westerley granite and Pennsylvania slate could be explained by the theory of dislocations.

Mason suggested two independent kinds of dissipation involved in the movements of dislocations. The frequency-independent dissipation is caused by the lattice vibrations set by the motions of the kink dislocations while the frequency-dependent dissipation is caused by the viscous drag on the motions of the dislocations.

For the frequency-dependent internal friction, we follow the method of Granato and Luche[2] by considering the motion of the dislocations. The momentum equation is:

$$\frac{\partial^2\sigma}{\partial x^2} \quad \frac{\rho\,\partial^2\sigma}{\lambda + 2\mu\,\partial t^2} \quad \frac{\Lambda\rho a}{\ell} \int_0^{\ell} \xi\, dy \qquad (1)$$

and the equation of motion of the dislocation is:

$$A\,\frac{\partial^2\xi}{\partial t^2} + B\,\frac{\partial\xi}{\partial t} - C\,\frac{\partial^2\xi}{\partial y^2} = a\sigma \qquad (2)$$

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[1] W. P. Mason, "Internal Friction at Low Frequencies Due to Dislocations: Applications to Metals and Rock Mechanics," Chapter 7 in Physical Acoustics, Principles and Methods, Vol. 8, edited by W. P. Mason and R. N. Thurston, Academic Press, New York (1971), 347-371.

[2] A. Granato and K. Luche, "Theory of Mechanical Damping due to Dislocations," J. Appl. Phys. 27 (1956), 583-593.

where ξ = displacement of dislocation line,

σ = applied stress,

$A = \pi \rho a^2$,

B = drag coefficient,

$C = \mu a^2/2$,

Λ = total length of movable dislocations

a = dislocation strength,

ℓ = loop length of dislocation,

μ, λ = Lame's constants,

subject to:

$$\xi(0, t) = \xi(\ell, t) = 0.$$

The internal friction and elastic modulus defect can be shown to be:

$$Q^{-1} = \frac{\Delta(\lambda + 2\mu)}{\lambda + 2\mu} \frac{\Omega}{D(1 - \Omega^2)} \tag{3}$$

and

$$\frac{\Delta(\lambda + 2\mu)}{\lambda + 2\mu} = \frac{8v^2 \Lambda \rho a^2 \ell^3}{c\pi^4} \frac{(1 - \Omega^2)}{(1 - \Omega^2)^2 + \Omega^2/D^2} \tag{4}$$

where

$\Delta(\lambda + 2\mu)$ = change in elastic modulus due to dislocations,

$\omega_o = \pi (C/A)^{1/2} \ell$

$D = \omega_o A/B$,

v = velocity of propagation,

$\Omega = \omega/\omega_o$

The frequency-independent part of Q^{-1} is given by Mason[1] as $\beta\Delta(\lambda + 2\mu)/(\lambda + 2\mu)$, where β is a constant. Hence the combined internal friction is:

$$Q^{-1} = \frac{\Delta(\lambda + 2\mu)}{\lambda + 2\mu} \left[\beta + \frac{\Omega}{D(1 - \Omega^2)}\right] \qquad (5)$$

The NASA (Huntsville) experiments (unpublished) gave the internal friction as:

Q^{-1} = 0.78 Neper at 100 KHz, and

Q^{-1} = 0.47 Neper at 250 KHz.

Hearst, et al.[2] give Q^{-1} = 0.05 for frequency below 500 Hz.

This model is able to account for the variation of the internal friction with frequency. However, due to insufficient data available, the validity of this model is to be verified with the experimental data to be obtained.

5.4. The Viscoelastic Model

The discussion on the viscous effect of fluid flow through the pores of a porous solid follows closely that of

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[1] W. P. Mason, "Internal Friction at Low Frequencies Due to Dislocations: Applications to Metals and Rock Mechanics," Chapter 7 in Physical Acoustics, Principles and Methods, Vol. 8, edited by W. P. Mason and R. N. Thurston, Academic Press, New York (1971), 347-371.

[2] J. R. Hearst et al., "Fractions Induced by a Constrained Explosion in Kemmerer Coal," Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 13 (1976), 37-44.

Biot.[1] Assuming that the pores in coal are of straight cylindrical tubes (the sinuosity and various geometric factors can be taken into account by multiplying the attenuation constant by a factor greater than 1), we can assume the flow in the porous coal is of the Poiseuille type if the frequencies used are less than:

$$f_t = \pi\upsilon/(4d^2)$$

where υ = dynamic viscosity of fluid,

d = diameter of the pore.

From Anderson et al.[2] and Gan et al.[3] we obtain the porosity of coal as 4% and the mean pore diameter as 500A.

For water, $\upsilon = 1.27 \times 10^{-6} m^2/s$, and taking $d = 500 \times 10^{-10} m$, then $f_t = 4 \times 10^{12}$ Hz. This shows that for the frequency range considered in this project, we can assume Poiseuille flow.

According to the Biot[4] model, the attenuation constant α may be expressed as:

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[1] M. A. Biot, "Theory of Propagation of Elastic Waves in a Fluid-Saturated Porous Solid. I. Low-Frequency Range," J. Acoust. Soc. Am. 28 (1956), 168-178.

[2] R. B. Anderson et al., "Sorption Studies on American Coals," J. Phys. Chem. 60 (1956), 1548-1558.

[3] H. Gan, S. P. Nandi and P. L. Walker, "Nature of Porosity in American Coals," Fuel 51 (Oct. 1972), 272-277.

[4] Biot, pp. 168-178.

$$\alpha = \frac{1}{2L_c} |\xi_1 \xi_2| \frac{p_{11}p_{22} - p_{12}^2}{r_{12} + r_{22}} \left(\frac{f}{f_c}\right)^2$$

in which f is the frequency, f_c is a characteristic frequency of oscillations in the pores, and all the other symbols represent physical properties of the elastic solid and the saturating fluid.

Using values for these parameters culled from the literature available,[1,2] for coal as the solid and water as the fluid, the following set of values is appropriate:

	p_{11}	=	0.80
	p_{22}	=	0.15
	p_{12}	=	0.025
	r_{11}	=	0.97
	r_{22}	=	0.06
	r_{12}	=	0.015
	V_c	=	2.3×10^3 m/sec
	f_c	=	2.6×10^{12} Hz
	L_c	=	1.4×10^{11} m
then	z_1	=	6.94
	z_2	=	0.058

[1]R. B. Anderson et al., "Sorption Studies on American Coals," J. Phys. Chem. 60 (1956), 1548-1558.

[2]H. Gan, P. Nandi and P. L. Walker, "Nature of Porosity in American Coals," Fuel 51 (Oct. 1972), 272-277.

$$\xi_1 = 5.94$$

$$\xi_2 = 0.942$$

For $f = 10^6$ Hz, we have

$$\alpha = 2.5 \times 10^{-4}\ m^{-1}$$

which is too small to have any significant effect on the observed attenuation constant.

5.5. Further Model to be Explored

As a consequence of the nature of coal formation[1] from organic substances, it is a layered material, the layers differing in their physical appearance and in their maceral content; the plane of the layers is known as the bedding plane. Measurements of internal surfaces have shown that coal is highly porous, the pore sizes ranging down to tens of angstroms. In addition, the coal is ramified with randomly distributed cracks of macroscopic and microscopic sizes.

No differences of elastic behavior were observed for the two directions parallel to the bedding plane, but the modulus obtained for the direction perpendicular to the bedding plane was significantly lower than for the parallel direction.

Terry et al.[2] drew [illegible] general conclusions from their

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[1] A. Granato and K. Luche, "Theory of Mechanical Damping Due to Dislocations," J. Appl. Phys. 27 (1956), 583-593.

[2] N. B. Terry and W. T. A. Morgans, "Studies of the Rheological Behavior of Coal," Section II, 13 in Mechanical Properties of Non-metallic Brittle Materials, edited by W. H. Walton, Interscience, New York (1958), 239-258.

stress-strain experiments:

a) Coal is elastically transversely isotropic with the axis of symmetry perpendicular to the bedding plane; and

b) The values of the strain intercepts indicate some anisotropy in the crack distribution.

To test the hypothesis that the anisotropy of coal is due to the anisotropic distribution of the cracks, Terry measured the velocity of sound through coal when it was subjected to applied pressure. At a stress of 1600 psi, when the cracks are closed or partially closed, the anisotropy was considerably reduced. The anisotropy is due, in the main, to flat, disc-like cracks of microscopic thickness, oriented with their flat surface parallel to the bedding plane.

Whitehurst[1] deduced that the structure of coal can be envisioned as a highly cross-linked amorphous polymer, which consists of a number of stable aggregates connected by relatively weak cross-links.

Larsen and Kovac[2] estimated the molecular weight for bituminous coals to be in the range of 1500-1800. Assuming that bituminous coals are composed of aromatic and hydroaromatic units linked together, the Heredy-Neuworth

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[1] D. D. Whitehurst, "A Primer on the Chemistry and Constitution of Coal," Chapter 1 in Organic Chemistry of Coal, edited by J. W. Larsen, American Chemical Society, Washington, D.C. (1978), 1-35.

[2] J. W. Larsen and J. Kovac, "Polymer Structure of Bituminous Coals," Ibid., Chapter 2, 36-49.

depolymerization is thought to cleave the alkyl chains linking the aromatic units. They estimated that the average cross-link chain contains 3-6 aromatic units.

Further effort will be directed in deriving a polymeric model for coal to explain the acoustic velocity and attenuation as a function of frequency at a fixed temperature.

Chapter VI

DEVELOPMENT OF SOFTWARE FOR MINI-COMPUTER ANALYSIS OF DATA FROM A DIGITAL OSCILLOSCOPE

by H. Joseph Venne, Jr.

6.1. Abstract

An assembly language computer program was developed to perform the task of transferring data from a Nicolet Model 1090A Explorer Digital Storage Oscilloscope through a Texas Instruments Model 980 Computer Input/Output Data Module to the memory of a Texas Instruments Model 980A Minicomputer. The purpose of the transfer was to enable the mathematical manipulation of data obtained from experiments aimed at determining the acoustic properties of coal. An assembly language computer program was developed to return the data from the computer memory, after manipulation, through the data module interface and to the digital oscilloscope for final display. A study of the operational characteristics of the data module and the logic of assembly language data transfer programming was made to facilitate the actual software development.

6.2. Introduction

This chapter describes the computer software developed to implement the transfer of data between a Texas Instruments Model 980A Minicomputer and a Nicolet Model 1090 Explorer Digital Storage Oscilloscope through a Texas Instruments

Model 980 Computer Input/Output Data Module. This transfer of data is needed so that mathematical computations can be performed on the data by the minicomputer system.

The data used is originally obtained from experiments designed to determine the acoustic properties of coal, using ultrasonic pulses transmitted through a coal slab immersed in a water buffer. To obtain the information necessary to perform the desired analysis, the signals received by the transducers after reflection and transmission from and through the coal are displayed on the digital oscilloscope. It is then necessary to transfer these digital signals through the data module interfacing system to the computer; the software developed is needed at this point to implement the transfer. Once the data is stored in the computer memory, the required mathematical manipulations can be carried out.

The types of manipulations to be performed are related to the characterization of the ultrasonic pulses, reflected or transmitted. First, to obtain an accurate representation of the pulse from a particular experiment, an averaging of the signals from a number of test runs can be performed. This will tend to smooth out any random variations in the signals. Next, various statistical calculations can be performed on the data, such as a correlation computation to determine if certain reflected or transmitted signals are correlated to the incident signals. The correlation computations could particularly improve the extraction of the transmitted signals from the background noise. Hence, the exact beginning and end of the pulses can be determined, which is essential to the characterization of the signals.

After calculations similar to those listed above have been performed, the data must be transferred back to the oscilloscope for display. This requires similar programming to implement the transfer through the data module interface as was developed earlier.

6.3. Installation of the Input/Output Module

The installation of the Input/Output Data Module simply consists of the soldering of the appropriate connections on the computer-oscilloscope interface and inserting the circuit board in the central processing unit Input/Output chassis of the computer. The required connections are shown in Figure 6.1.

The options selected for usage in the module are as follows:

1. Module address. Connection E3-E4, E7-E8 for hexadecimal address 48.
2. No output driver pull-up resistor option.
3. No input interrupt option -E18-E19 connection to disable.
4. No data input line termination option.
5. External +5 volt output connected to the integrated circuits.
6. Output register reset enabled by the module reset.

The module was inserted in chassis I05.

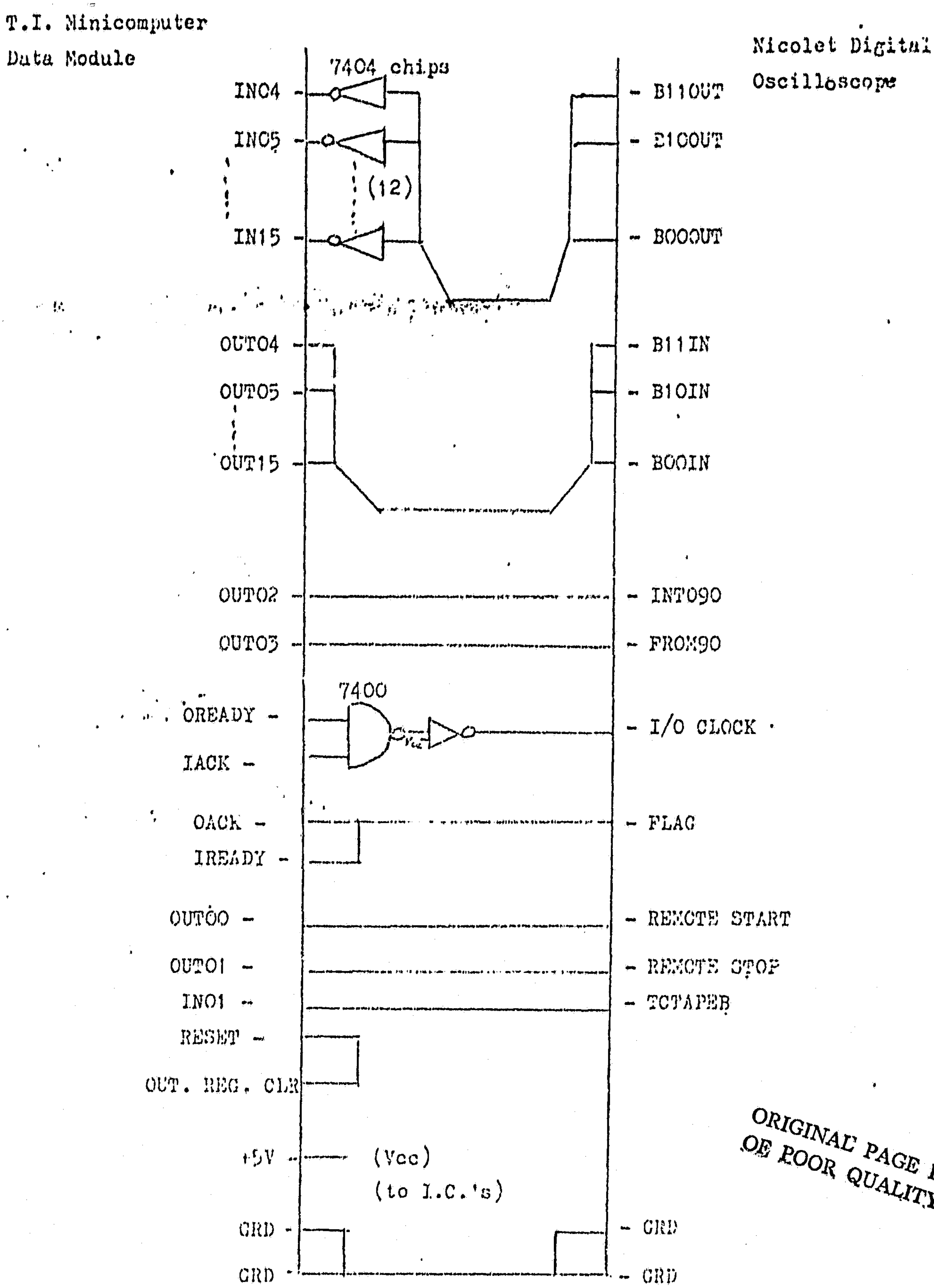

Figure 6.1. Connection of I/O Module to Oscilloscope.

6.4. Input/Output Data Module[1]

The Texas Instruments Model 980 Input/Output Data Module is a general purpose interface used for implementing data transfer between the Input/Output bus of the Model 980A computer and an external peripheral device, in this case a digital oscilloscope. It provides 16 input and 16 output lines for the data transfer. In addition to the general Input/Output Characteristics, the module also has the following options for user selection:

1. Module address. The module address has sixteen possible hexadecimal codes for user preference.

2. Output driver pull-up resistor voltage. The output driver circuits have the option of being attached to either +5 volts or up to 30 volts maximum supplied through 1,000 ohm, 1/4 watt pull-up resistors.

3. Input interrupt option. When connected, the input data bit 0 becomes an interrupt control line that is independent of program control.

4. Data input line termination. The data input line termination input impedances are adjustable as desired by the user.

5. External +5 volt output. A +5 volt output is available for external devices.

6. Output register reset. The module's register reset can be activated by the Input/Output bus reset, if desired, rather than by program control.

The Input/Output Data Module external device interconnection occurs at the top edge of the module circuit

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[1]Model 980 Computer Input/Output Data Module User's Manual, #965956-9701, Texas Instruments Incorporated, April 1, 1976.

board. There is a total of 48 pin assignments which are summarized below:

OUT(00-15)	- 16 output lines with data inversion occurring at the interface.
IN(00-15)	- 16 input lines with unchanged data logic at the interface.
OREADY	- Output ready line indicates that the module has a new data word ready for the external device; active at logic 0.
OACK	- Output acknowledge indicates that the external device has accepted the data word; active at logic 0.
IREADY	- Input ready indicates that the external device has an input word ready for the computer central processing unit; active at logic 0.
IACK	- Input acknowledge indicates that input data has been accepted by the central processing unit; active at logic 0.
+5 Volts	- Can be used to supply voltage for an external device.
VccEXT	- Can be used in output driver pull-up resistor circuits.
RESET and OUTRESET	- Both functions can be controlled by the resistor reset rather than by program control, if desired.
GRD	- 10 ground lines are available.

The pin numbers for the above connections can be found in the Input/Output User's Manual.[1]

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[1]Model 980 Computer Input/Output Data Module User's Manual, #965956-9701, Texas Instruments Incorporated, April 1, 1976.

6.5. Programming for Transfer of Data

The transfer of data from the computer to the oscilloscope is defined as a writing operation while the transfer of data from the oscilloscope to the computer is defined as a reading operation. These two operations must be performed by the user as the data module interfacing system is totally externally controlled. The read and write operations follow basically the same type of logic and can be implemented manually or by an assembly language program.

6.5.1. Logic of Read Operation[1]

The operation of a read function centers around the enabling and disabling of the input interrupt. The reading of data from the oscilloscope occurs when the input interrupt has been enabled and the data module signals an IREADY, or Input Ready, to signify that data is available for transfer. At this time, an input interrupt occurs and the channel is opened for the transfer of data to the CPU. In effect, the input interrupt feature interrupts the execution of whatever task the computer is performing and routes computer action to data transfer. When the data has been transferred, the CPU signals an INACK, or Input Acknowledge, to signify that the data has been accepted and the procedure is repeated.

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[1] Model 980 Computer Input/Output Data Module User's Manual, #965956-9701, Texas Instruments Incorporated, April 1, 1976.

A flow diagram for the procedure is given in Figure 6.2.

6.5.2. Generation Information Regarding Manual Input and Output of Data[1]

Single word transfers between the computer and oscilloscope through the 1/0 Data Module can be performed by executing the Write Direct Single (WDS) or Read Direct Single (RDS) instructions. The general format to be used for these instructions involves use of the sixteen data switches located on the computer front panel with significance as shown below:

Word 1

Bit	0	1	2	3	4	5 6	7	8	9	10	11 - 15
Code	1	1	0	1	1	group	0	0	E R	R/W	external register

operation code

R/W: logic 0 RDS, logic 1 WDS

Word 2

Bit	0 7	8	9	10	11	12	13-15
Code	unused	B	O	I	D	A	R

The first word is used to determine the operation used (Read or Write) and the number assigned to the external register that represents the address of the data module. The group field identifies the chassis containing the I/O

[1]Model 980 Computer Input/Output Data Module User's Manual, #965956-9701, Texas Instruments Incorporated, April 1, 1976.

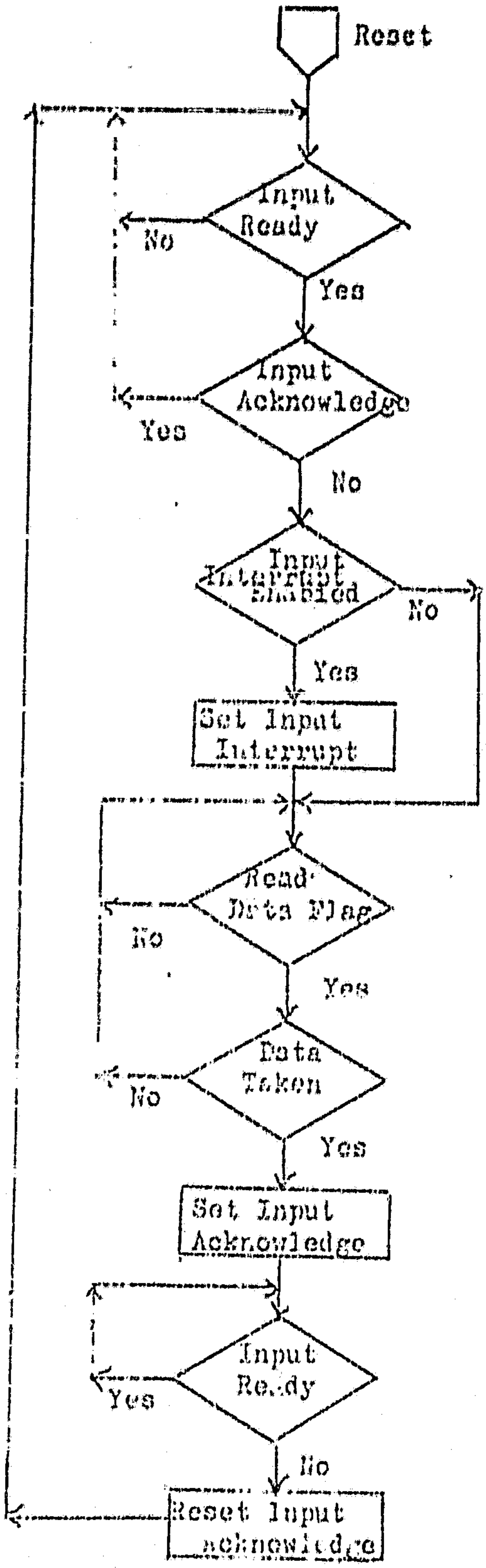

Figure 6.2. Flow Chart for Reading Input.

module. The second word is used to determine the source or destination of the data word and selects the features to be used in the transfer, such as skip on ready, decrement data address, and increment data address. The functions of the bits of word 2 are given below:

Bit	Symbol	Function
8	B	Busy bit or skip on ready feature provides the option of executing other instructions if the data is not ready for transfer when requested by the CPU - logic 1 and sucessful data transfer results in the next instruction being skipped -logic 1 and no transfer results in the next instruction being executed.
13-15	R	Specifies the internal register used in the operation.
12	A	Logic 0 - data transferred to or from register R. Logic 1 - data transferred to or from memory location R.
11	D	Not used for the 980A model.
10	I	Logic 1 and A = logic 1 - address specified by R is incremented by 1 each time a transfer occurs. Logic 0 - a decrement occurs.

6.5.3. Manual Read Operation[1]

To transfer data manually from the oscilloscope to the computer, the following read operations are available as defined by word 1:

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[1]Model 980 Computer Input/Output Data Module User's Manual, #965956-9701, Texas Instruments Incorporated, April 1, 1976.

Instruction	Bit 10	Bits 9,11,12,13	Bit 14	Bit 15	Function
RDS	0	Module address	0	0	read status
RDS	0		0	1	input data
RDS	0		1	0	read output register

The description of the read operations is given below:

read status - provides the CPU with the current operational mode of the controller;

The bits used are as follows:

Bit	Function
0, 9-15	Not used.
1	Output interrupt enable status. OI = logic 1 - enabled. OI = logic 0 - disabled.
2	Input interrupt enable status. II = logic 1 - enabled. II = logic 0 - disabled.
3	Output interrupt status OS = logic 1 - interrupt is pending.
4	Input interrupt status IS = logic 1 - input interrupt is pending.
5	Output ready signal status OR = logic 1 - output word is ready for the external device and the acknowledgement has not been received.
6	Output acknowledge signal status. OA = logic 1 - output acknowledge has been received.
7	Input ready signal status. IR = logic 1 - external device has input ready for the Data Module.
8	Input acknowledge signal status. IA = logic 1 - input from external device is acknowledged.

Bit	Function
Input data	- permits the transfer of a 16 bit word from the external device to the CPU.
Read output	- permits the transfer of the output data register information into the CPU.

To perform the data transfer one follows the general flow diagram of Figure 6.2 and enters data words with the above format to enact the transfer. In general, one uses the read status option to determine if the input interrupt is in action; then uses the input data option to transfer a word; then uses the read status option to determine when the computer acknowledges the data transfer and then repeats the process. This method allows one to experience the actual mechanical operation of the computer but is quite inefficient for the transfer of large amounts of data.

6.5.4. Programmed Read Operation[1]

The program that follows is used to read a 4096 word buffer from the oscilloscope through the I/O Data Module Interface which has an address of 48. 4096 words are read since the data from the experiment performed to determine

[1]Model 980 Computer Input/Output Data Module User's Manual, #965956-9701, Texas Instruments Incorporated, April 1, 1976; Model 980A Computer Assembly Language Input/Output Manual, #9?1961-9734, Texas Instruments Incorporated, April 1, 1973; Model 980 Computer Assembly Language Programmer's Reference Manual #943013-9701, Texas Instruments Incorporated, March 1, 1975; C. Foster Caxton, Programming a Micro-Computer, Addison-Wesley Publishing Co., Reading, Massachusetts, 1978.

the acoustic properties of coal are represented as 4096 words in the oscilloscope memory. The program follows the flow diagram given in Figure 6.2.with the addition of a loop during the interrupt sequence that allows the implementation of other programming while the computer is waiting for a data word to be ready for transfer. The program has a checking procedure to determine if the interrupt has been presented to the computer from the data module and not from some other system module. Buffer overflow is prevented. This program uses the input interrupt system so that the system can perform other tasks while waiting for the interrupt to occur.

LABEL	OPERATOR	OPERAND	COMMENT
1	8	13	30 - column #
A	EQU	0	assign registers
X	EQU	2	
DATAWD	EQU	>49	
CNTRL	EQU	>48	
RSTATS	EQU	>48	
BEGIN	@LDA	=55B	set up interrupt sequence
	@STA	>6	
	@LDA	=TRAP	
	@STA	>7	
	@LDA	=0	
	STA	RDCNTR	initialize system
	@LDA	=>2000	
	WDS	CNTRL	enable input interrupt

LABEL	OPERATOR	OPERAND	COMMENT
	DATA	0	send contents of register
TRAP	DATA	0,0	loop for checking interrupts
1	8	13	30 - column #
	STA	TEMP	
	STX	TEMP + 1	
	RDS	RSTATS	
	DATA	>0	
	TABO	2	check interrupt enable
	BRU	OTHER	if not enabled branch to
	LDA	RDCNTR	other programming
	CPL	=4096	if interrupted do data transfer
	SNE		
	BRU	ERRT	
	RMD	A,X	
	RDS	DATAWD	
	DATA	>0	
	STA	RDBUFFER X	
	LDA	TEMP	
	LDX	TEMP + 1	
	IMO	RDCNTR	
	LSB	TRAP	return for next data read sequence
OTHER			other programming
RDBUFR	BSS	4096	
TEMP	DATA	0,0	
RDCNTR	DATA	0	
	END	BEGIN	

/*
/*
/*

6.5.5. Write Operation

6.5.5.1. Logic of Write Operation. The operation of the write function centers around the enabling and disabling of the output interrupt. Writing data to an external device occurs when the output interrupt has been enabled and the CPU issues an OREADY, or Output Ready, signal to signify that data is ready for transfer. At this point, the output interrupt occurs and the data is transferred to the external device. When the external device signals an OACK, or output acknowledge, to signify that the data has been accepted, the process repeats. A flow diagram for the procedure is given in Figure 6.3. This flow procedure does not follow the output interrupt directly but loops to check the output ready and output acknowledge bits directly to implement the data transfer.

6.5.5.2. Manual Write Operation.[1] The manual write operation uses the same word format given in Section 6.5.2 with the write operation defined in word 1 as follows:

Instruction	Bit 10	Bits 9,11,12,13	Bit 14	Bit 15	Function
WDS	1	module address	0	0	control
WDS	1		0	1	output word
WDS	1		1	0	output bit

The write functions are defined below:

[1] Model 980 Computer Input/Output Data Module User's Manual, #965956-9701, Texas Instruments Incorporated, April 1, 1976.

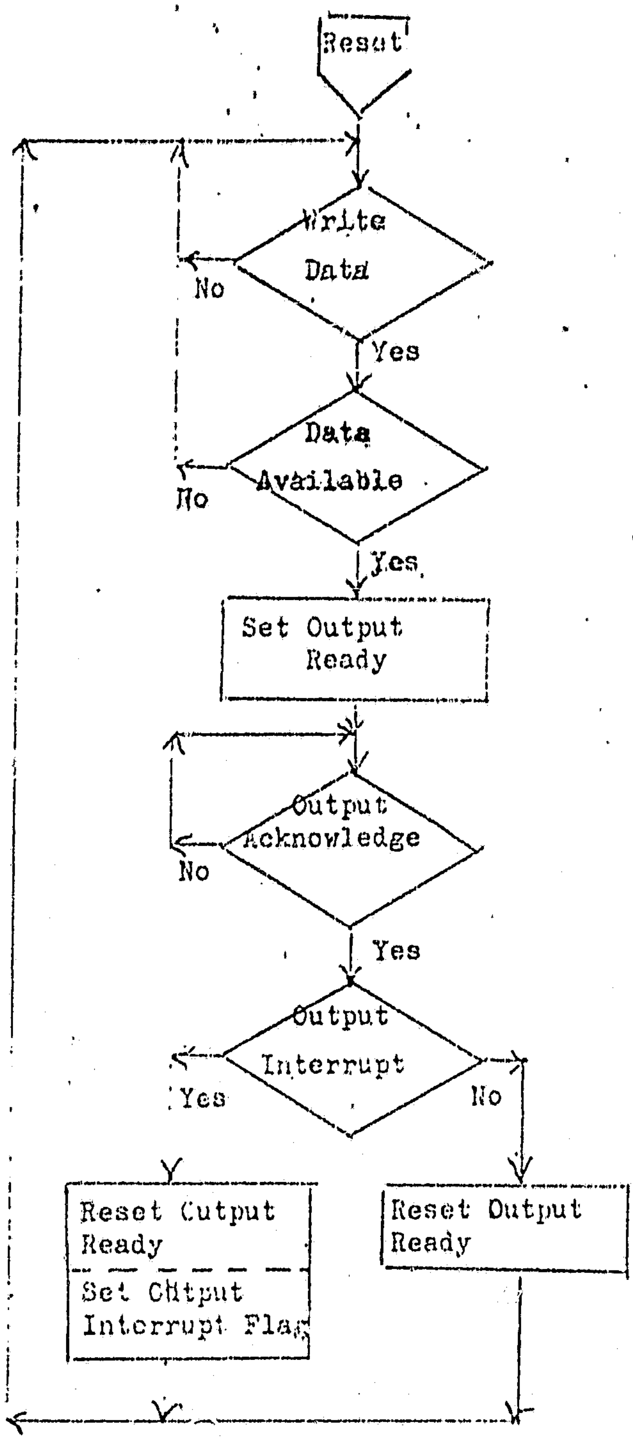

Figure 6.3. Flow Chart for Writing Output.

Control - This instruction uses the first three bits of the data word to initialize the I/O module.

bit 0 - logic 1 - all control logic and flags are reset.

bit 1 - output interrupt enable.

OI = logic 1 - interrupt issued when data transfer is acknowledged.

OI = logic 0 - no interrupt issued.

bit 2 - input interrupt enable.

II = logic 1 - interrupt issued when data word is ready for transfer.

II = logic 0 - no interrupt issued.

<u>output word</u> - transfer a 16 bit word from the CPU to the Data Module

<u>output bit</u> - permits loading of a single bit of the output register with a specified value.

Again, to implement the write operation, one checks the device status with the read status options, as described above, and then transfers the data at the appropriate time. Also, as stated before, this is not a very efficient way to enact a large number of data transfers.

6.5.5.3. <u>Programmed Write Operation</u>. The following program is used for the transferral of a 4096 word buffer from the computer to the oscilloscope through the I/O Data Module interface. The program follows the flow diagram given in Figure 6.3 and manual write operation described above.

```
LABEL     OPERATOR   OPERAND    COMMENT
1         8          13         30 - column #
X         EQU        2          assign registers
A         EQU        0
WDATA     EQU        >49
RSTATS    EQU        >48
CNTRL     EQU        >48
BSS       EQU        >D8C0
BEGIN     LDA        =>8000
          WDS        CNTRL      reset system
          DATA       0
          LDA        =BUFFER
          LDX        =-4096     set up counter
LOOP      WDS        WDATA      write data word if ready
          DATA       >00A8      test busy bit if busy
          BRU        LOOP       loop back and try again
1         8          13         30 - column #
          STA        SAVE
          RDS        RSTATS
          DATA       >0
          TABZ       6          check if output acknowledged
          BRU        $-3        if no  wait
          LDA        SAVE       if yes  loop back
          BIX        LOOP       to send next word
BUFFER    BSS        4096
SAVE      DATA       0
          END        BEGIN
/*
/*
/*
```

6.6. Implementation of Program[1]

With the completion of the writing of the appropriate read and write programs, the actual transfer of data may be performed. This involves the operation of the computer itself and the use of the high speed reader, teletype, and pre-punched system tapes. The procedure consists of making the computer operational, enabling the system to create a program, creating the program, creating a tape for running the program, and running the program. The steps are as follows:

6.6.1. System Start-Up

1. Turn on power.
2. Select Halt and Reset.
3. Set data switches to '000F'; select Enter in PC.
4. Select Run and Load; computer should run to idle; select Reset.
5. Turn tape reader On, Load; load PTR System Loader tape in reader; turn reader on Run.
6. Set switches to '0000', enter in M; set '0004' and enter in PC; select Run and Load; tape should read in and stop; display M; if result is not '0000', rewind, Reset and repeat.
7. Load "IOP#1 - Class III System, Configuration II" tape in reader, select Start; when tape has been read, Display M, result should be '0000'.
8. Turn teletype on 'Line', select Start; teletype

---

[1] Model 980A Computer Basic System Use and Operation Manual, #961961-9710, Texas Instruments Incorporated, August 15, 1972.

should respond *Ready*; operating system is now in place and can be restarted by selecting Halt, Reset, Run, and Load.

6.6.2. Create Source Tape

1. Assign units by typing the following on the teletype:

   //ASSIGN,4,KEY.
   //ASSIGN,5,HSR.
   //ASSIGN,6,KEY.
   //ASSIGN,7,TTP.
   //ASSIGN,8,KEY.

2. Load "Source Editor" tape.

3. Type //EXECUTE,HSPT.

4. Tape will read in and the response will be '?'

5. Enter text mode by typing '*'.

6. Type in the read or write program.

7. After last line return to control mode by returning the carriage.

8. Type S+N where N is the number of lines in the program.

9. Source tape will be punched by the system.

6.6.3. Run Program

1. Repeat system start-up method through step #6.

2. Load object tape.

3. Select Run and Start on the 980A panel.

4. Select start after the object tape is read and the read or write program is in execution.

At this point, the program is in the computer and steps described above for the transfer of data will be implemented by the computer.

6.7. Conclusions and Results

If the procedures outlined above are followed, the successful transfer of data between the oscilloscope and computer through the Input/Output Data Module will be achieved. Thus, with further programming, the analysis of the data obtained from the experiments carried out can also be performed and the furthering of the knowledge of the acoustic properties of coal can be achieved. The above programming and methodology were extracted from a series of user manuals covering the Texas Instruments Model 980A computer as cited in the footnotes. Explanation of the assembly language computer statements can be found in these manuals along with an elaboration of editing and debugging the programs.

Chapter VII

CONCLUSIONS

The most significant achievement during the present contract period has been the design and construction of the digital sine wave generator, which is expected to play a central role in subsequent experimental measurements. This device has been employed in some measurements of wave speed and attenuation rates for coal samples, using a relatively crude measurement technique. The results of these tests are in reasonably good agreement with the small amount of available data.

Other efforts during this period have been directed towards developing analytical capabilities to support the use of the digital generator in more extensive experimental measurements and theoretical models which will allow extension of the results of the measurements beyond the ranges of parameters, particularly the signal frequency, for which experiments can be performed. It is anticipated that, in the subsequent phase of this project, it will be possible to proceed rapidly with the experimental measurements in view of foundations which have been established in the current period.

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