

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Handwritten initials/signature

Date: 8/17/78

Project Title: Applications of Acoustics in the Measurement of Coal Slab Thicknesses

Project No: E-25-609

Co-Project Directors: Dr. Allan D. Pierce; Dr. W. James Hadden, Jr.; and Dr. John M. Mills

Sponsor: NASA; George C. Marshall Space Flight Center; MSFC, AL 35812

Agreement Period: From 7/31/78 Until 7/30/79 (Contract Period)

Type Agreement: Contract No. NAS8-33093

Amount: \$87,636

Reports Required: Monthly Progress Reports; Foreign Trip Reports; Final Report

Sponsor Contact Person (s):

Technical Matters

(Contracting Officer Representative)
B.R. Reed
EC 33
NASA
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

205/453-1583

Alternates: J. L. Randall, EC 31, 205/453-4620
F. A. Cagle, EM 63, 205/453-1865

Contractual Matters

(thru OCA)

Office of Naval Research
Resident Representative
325 Hinman Research Building
Campus

Defense Priority Rating: DO-C9 under DMS Reg. 1

Assigned to: Mechanical Engineering (School/Laboratory)

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GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT TERMINATION

Date: June 10, 1980

Project Title: Applications of Acoustics in the Measurement of Coal Slab Thickness

Project No: E-25-609

Co-Project Director: Dr. Allan D. Pierce; Dr. W. James Hadden, Jr.; and Dr. John M. Mills

Sponsor: NASA; George C. Marshall Space Flight Center; MSFC, AL 35812.

Effective Termination Date: 10-31-79

Clearance of Accounting Charges: 10-31-79

Grant/Contract Closeout Actions Remaining:

- Final Invoice and Closing Documents
- Final Fiscal Report
- Final Report of Inventions
- Govt. Property Inventory & Related Certificate
- Classified Material Certificate
- Other _____

Assigned to: Mechanical Engineering (School/Laboratory)

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GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Applications of Acoustics in the
Measurement of Coal Slab
Thickness

Monthly Progress Report No. 1
for the Period:
Aug. 1, 1978 through Aug. 31, 1978

Contract No: NAS8-33093

Prepared for:
George C. Marshall Space Flight Center
Marshall Space Flight Center,
Alabama 35812

Prepared by:
Dr. John M. Mills,
Co-Investigator

Date
Aug. 31, 1978

Re: Applications of Acoustics in the Measurement of Coal
Slab Thickness

Contract No. NAS8-33093

ITEM: Progress Report No. 1

DATE: August 31, 1978

PROGRESS TO DATE

Project has been initiated at School of Mechanical Engineering, Georgia Tech, and appropriate project accounts are being opened to cover project expenditures.

Arrangements have been made by B. R. Reed, EC33, NASA/Marshall Space Flight Center for shipment of Government Furnished Property (as specified under Art. VII, A of above referenced contract) to be shipped to Georgia Tech School of Mechanical Engineering.

Dr. Mills has reviewed preliminary designs for phase-controlled signal source and is preparing final specifications for this equipment. The signal source will include both stock components (e.g., R.F. amplifiers) and specially designed components: waveform generators, timing circuits, transducers, and sample fixtures.

CURRENT PROBLEMS

No problems have arisen to date.

WORK PROJECTED FOR NEXT REPORTING PERIOD

Government-furnished signal sources and other equipment will be tested upon receipt at Georgia Tech. These tests will use homogeneous samples (e.g. metals and plastics) to verify the operation of the equipment and to familiarize the research staff with it.

Co-investigators will meet with Sponsor Contact Persons (Reed, et al) at NASA/Marshall to discuss project objectives and initial research phases.

Requests will be filed per contract terms (Art. XVI - ACQUISITION OF EXISTING GOVERNMENT EQUIPMENT) for such stock components of the signal source as may be appropriate. Work on final design of the signal source will continue through this period.

EXPENDITURES TO DATE

Item:

Amount:

DIRECT SALARY AND OVERHEAD:

Dr. Mills: month
 of August, 1978.

\$1,722.00

ANTICIPATED PROBLEMS:

None, to date

FORECAST OF FUNDS REQUIRED:

Per Contract balance.

E-25-609

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Applications of Acoustics in the
Measurements of Coal Slab Thickness

Monthly Progress Report No. 2
for the Period
September 1, 1978 through September 30, 1978

Contract No: NAS8-33093

Prepared for:

George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35812

Prepared by:

Dr. John Mills
Co-Investigator

Date

October 12, 1978

RE: Applications of Acoustics in the Measurements of Coal Slab
Thickness

ITEM: Progress Report No. 2

DATE: October 12, 1978

PROGRESS TO DATE

A graduate student Mr. Carolus has been assigned to work on the project, and is being supported as a Graduate Research Assistant. Two other self supported graduate students, Messrs. Chew and Pettyjohn, are also working on studies related to the project.

Circuit drawings are now being prepared for digital signal generators, and components for prototpye circuits are now on order.

Instrumentation and transducers as specified in the contract have been received from NASA/Marshall. The Nicolet digital oscilloscope (model 1090A) was not delivered in working condition, but has been repaired and approximately calibrated. It appears possible that this oscilloscope can be interfaced directly to the digital computer. If so, there may be no necessity of acquiring any other oscilloscope for the project as had been suggested in the original proposal. Advice of the Nicolet Corp. is being sought in this connection.

Dr. Mills visited NASA/Marshall to discuss the project with B.R. Reed, J.L. Randall, et al, of the sponsering group. Discussion covered basic problems anticipated in both preliminary measurements of properties of coal, and eventual problems in development of possible resulting Coal Interface Detection (CID). Similarities are apparent between acoustic and electromagnetic studies, particularly in the area of signal detection and processing. A sample of coal from Brucetown was given to the Georgia Tech group by NASA/Marshall.

CURRENT PROBLEMS

No problems have arisen to date.

WORK PROJECTED FOR NEXT REPORTING PERIOD

Prototype circuits will be built and tested for the waveform generators and counters. Pending successful prototyping, final designs for the corresponding sections of the digital signal source will be completed and constructed.

Transducers and pulse generators supplied by NASA/Marshall will be tested with calibration samples.

Pending information from Nicolet Corp., specifications for interfacing between the digital oscilloscope and a School of Mechanical Engineering minicomputer will be prepared.

Stock components (e.g. R.F. amplifiers) for the pulse cancellation system will be specified.

ANTICIPATED PROBLEMS

None to date.

FORECAST OF FUNDS REQUIRED

Per Contract Balance.

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Applications of Acoustics in the
Measurement of Coal Slab
Thickness

Monthly Progress Report No. 3
for the Period:
Oct. 1, 1978 through Oct. 31, 1978

Contract No. NAS8-33093

Prepared for:
George C. Marshall Space Flight Center
Marshall Space Flight Center,
Alabama 35812

Prepared by:
Dr. Allan D. Pierce
Co-Investigator

Date
Nov. 13, 1978

Re: Applications of Acoustics in the Measurement of Coal Slab Thickness

Contract No. NAS8-33093

ITEM: Progress Report No. 3

DATE: November 13, 1978

PROGRESS TO DATE

During the past month, considerable time was spent becoming familiar with the NASA equipment received the previous month.

The circuit diagrams mentioned in the previous report have now been completed. The digital sine wave generator has been assembled on a laboratory bread board and has been tested up to 5 MHz. The crystal clock has been designed and is ready for testing.

A graduate student Mr. Chew, Chye Heng, is working on the design of the underwater test cell for the experiments.

Dr. Mills is presently doing an error analysis study concerning the precision to which the phases of the transducers may be controlled.

CURRENT PROBLEMS

No problems have arisen to date.

WORK PROJECTED FOR NEXT REPORTING PERIOD

It is anticipated the sound speed measurement system will be assembled and ready for testing by the end of the next reporting period.

EXPENDITURES TO DATE

It is estimated that approximately \$15,000 has been expended up to the present time.

ANTICIPATED PROBLEMS

None to date.

FORECAST OF FUNDS REQUIRED

Per contract balance.

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Applications of Acoustics in the
Measurement of Coal Slab
Thickness

Monthly Progress Report No. 4
for the Period
Nov. 1, 1978 through Nov. 30, 1978

Contract No. NAS8-33093

Prepared for:

George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama 35812

Prepared by:
Dr. W. James Hadden, Jr.
Co-Investigator

Date
Dec. 20, 1978

Re: Applications of Acoustics in the Measurement of Coal Slab Thickness
Contract No. NAS8-33093

Item: Progress Report No. 4

Date: December 20, 1978

PROGRESS TO DATE

Progress on the subject contract continued along the lines described in previous reports. Testing of the crystal clock has begun. Dr. Mills has concluded his analysis of the precision with which the transducers can be controlled.

Mr. Chew Chye Heng has completed the design of the underwater test cell for the sound speed measurements. A sketch of the test cell is appended hereto. The salient features of the design are: i) a solid mounting plate (thickness $\frac{1}{4}$ inch) which in addition to holding the sample, will prevent diffracted sound from reaching the receiving transducer; ii) provision for varying the position of the sample between the transducers, which are fixed. Fabrication of the test cell has begun.

CURRENT PROBELMS

No problems have arisen to date.

WORK PROJECTED FOR NEXT REPORTING PERIOD

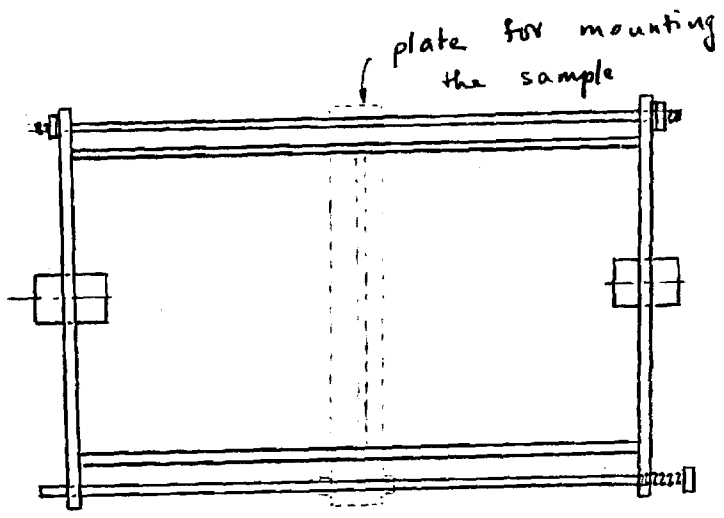
It is anticipated the sound speed measurement system will be assembled and ready for testing by the end of the next reporting period.

ANTICIPATED PROBLEMS

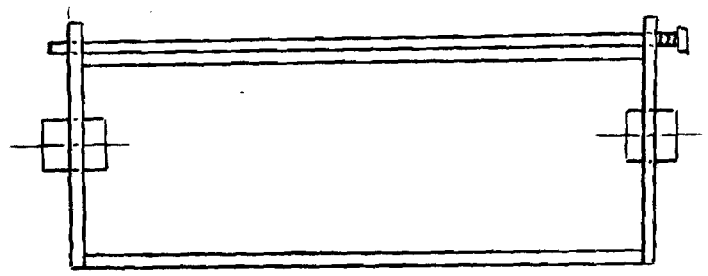
None to date.

FORECAST OF FUNDS REQUIRED

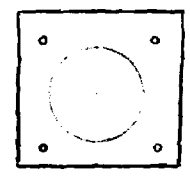
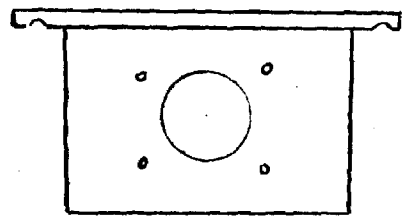
Per contract balance.



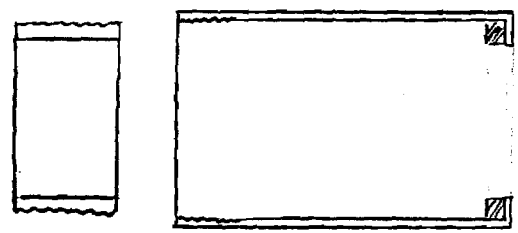
plan



elevation



mounting plate



Fixture for transducer

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Applications of Acoustics in the
Measurement of Coal Slab
Thickness

Monthly Progress Report No. 5
for the period
Dec. 1, 1978 through Dec. 31, 1978

Contract No. NAS8-33093

Prepared for:
George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama

Prepared by:
W. James Hadden, Jr.
Co-Investigator

Date

March 12, 1979

Re: Applications of Acoustics in the Measurement of Coal Slab Thickness
Contract No. NAS8-33093

Item: Progress Report No. 5

Date: February 14, 1979

PROGRESS TO DATE

In the month of December work was interrupted by the Christmas Holidays during which Georgia Institute of Technology was closed for ten days. Vacation time was taken during the month as well.

Mr. Chew Chye Heng began construction of the underwater test cell for the sound speed measurements. Assembly of the electronic circuits for the experimentation got under way.

CURRENT PROBLEMS

No problems have arisen to date.

WORK PROJECTED FOR THE NEXT REPORTING PERIOD

It is anticipated that testing of the sound speed measurement system will be in progress.

ANTICIPATED PROBLEMS

None to date.

FORECAST OF FUNDS REQUIRED

Per contract balance.

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Applications of Acoustics in the
Measurement of Coal Slab
Thickness

Monthly Progress Report No. 6
for the period
Jan. 2, 1979 through Feb. 28, 1979

Contract No. NAS8-33093

Prepared for:
George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama

Prepared by:
W. James Hadden, Jr.
Co-Investigator

March 12, 1979

Re: Applications of Acoustics in the Measurement of Coal Slab Thickness
Contract No. NAS8-33093

Item: Progress Report No. 6

Date: February 14, 1979

PROGRESS TO DATE

This report covers the period January 2, 1979 to February 28, 1979. It contains a summary of progress during this interval and a review of the experimental procedure. During this period the test cell for acoustic propagation measurements was constructed. A photograph of the cell and specimen holder is attached to this report. In addition testing and adjustment continued on the digital circuitry for controlling the timing and amplitudes of the pulses to be applied to the transducers. Exploratory tests were made in the test cell using a clear plastic sample instead of coal. During the course of these tests it was discovered that one of the 0.5 MHz transducers is faulty. Plans have been made to present three talks at the 50th Anniversary Meeting of the Acoustical Society of America in Cambridge, Massachusetts, in June 1979. Abstracts for these presentations are appended here to.

The following is a review of the experimental procedure we plan to employ in measurements of the ultrasonic properties of coal. This review is adapted from the proposal for the subject contract. The first section, which outlines the theoretical basis for the experiments, mentions the possibility of using solid buffer rods between the transducers and the sample: We have decided that a water buffer is preferable, because fabrication of the test cell is simpler and because the resulting signals are more readily analyzed.

Re: Applications of Acoustics in the Measurement of Coal Slab Thickness
Contract No. NAS8-33093

Item: Progress Report No. 5

Date: February 14, 1979

PROGRESS TO DATE

In the month of December work was interrupted by the Christmas Holidays during which Georgia Institute of Technology was closed for ten days. Vacation time was taken during the month as well.

Mr. Chew Chye Heng began construction of the underwater test cell for the sound speed measurements. Assembly of the electronic circuits for the experimentation got under way.

CURRENT PROBLEMS

No problems have arisen to date.

WORK PROJECTED FOR THE NEXT REPORTING PERIOD

It is anticipated that testing of the sound speed measurement system will be in progress.

ANTICIPATED PROBLEMS

None to date.

FORECAST OF FUNDS REQUIRED

Per contract balance.

We propose to base our investigation of the acoustic properties of coal on the configurations of transducers and samples³ shown in Figs. 1a and 1b. In Fig. 1a, the sample is suspended in a liquid bath between two transducers. The liquid should be chosen such that its characteristic impedance is not too dissimilar from that of coal; tentatively, water should be adequate. In the system shown in Fig. 1b, the liquid bath is replaced by a pair of buffer rods, the transducers being attached to the ends of the buffer rods. We anticipate that the water-bath configuration will be the best choice of the two.

The technique we propose to employ is an echo cancellation method which is based on the following analytical model. As sketched in Fig. 2a, we first consider plane waves at normal incidence from a buffer material (liquid or solid) impinging on a slab of coal, which is backed by a second long region of buffer material. The buffer material is characterized by its acoustic wave number k and characteristic impedance Z_B . The coal slab has thickness ℓ , wavenumber k_C , and characteristic impedance Z_C . (The latter two quantities are complex numbers.) Assuming that conservation of momentum in each part of the system is expressed by the equation

$$\rho \frac{\partial v_x}{\partial t} = \frac{\partial \sigma_{xx}}{\partial x} \quad (1)$$

and representing the particle velocity and the stress as

$$v_x = \text{Re}[\hat{v}_x e^{-i\omega t}] ; \quad \sigma_{xx} = \text{Re}[\hat{\sigma} e^{-i\omega t}] \quad (2)$$

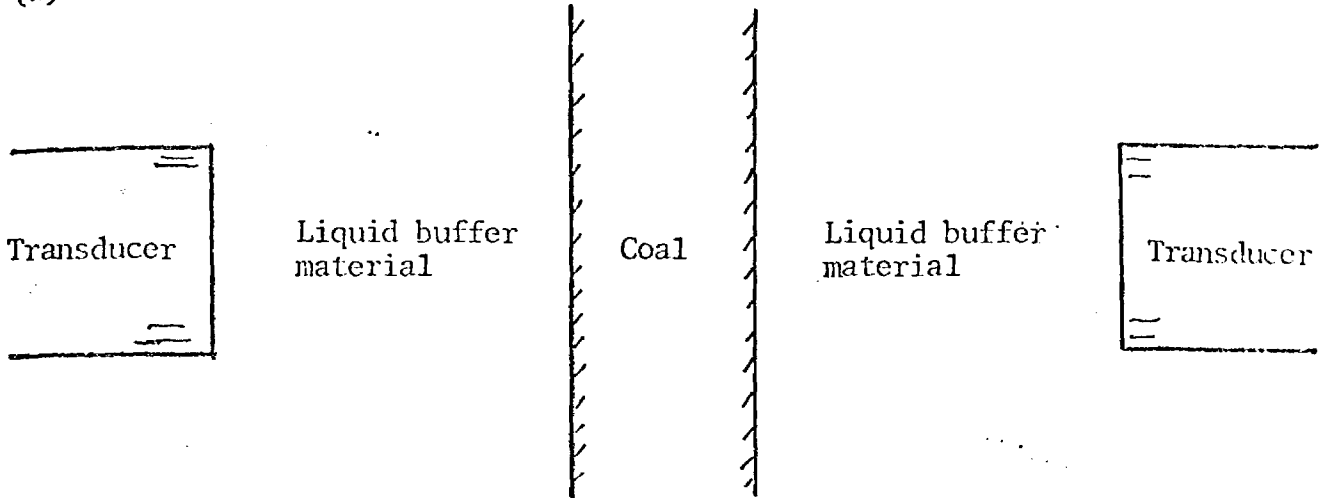
we determine that, if

$$\hat{\sigma} = A e^{ikx} \quad (3)$$

and

$$\hat{v}_x = -\hat{\sigma}/Z \quad (4)$$

(a)



(b)

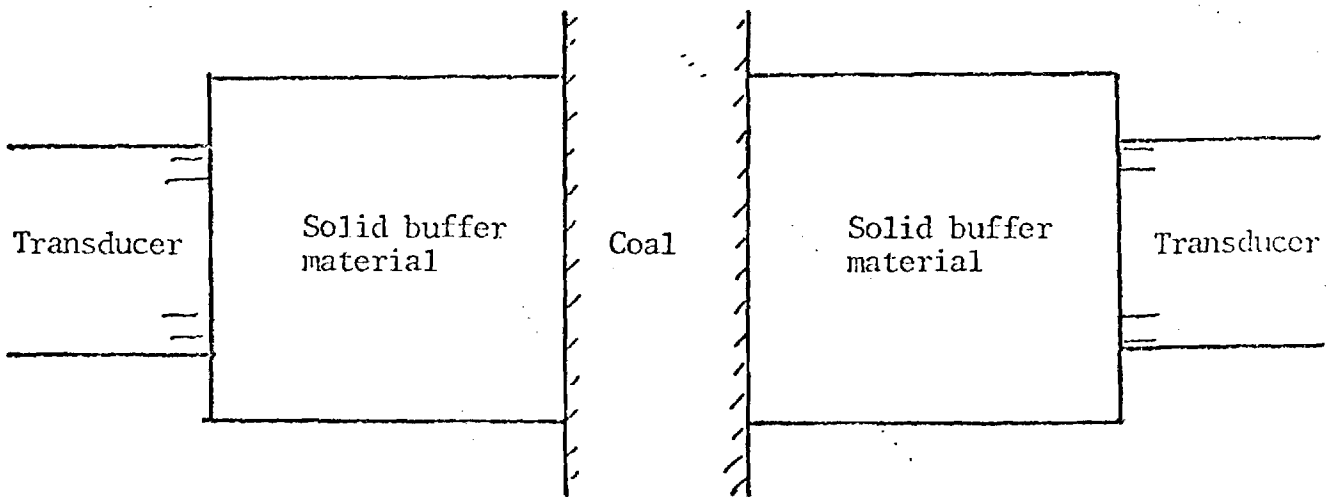


Figure 1. Possible experimental configurations for the measurement of the acoustical properties of coal.

then Eq. (1) implies that

$$Z = \rho \omega / k \quad (5)$$

gives the proper relation between characteristic impedance, mass density, angular frequency, and wavenumber. The above holds even if k is complex (as is the case when sound propagation is attenuated with increasing propagation distance).

For the model indicated in Fig. 2a, the incident plane wave, assumed to have unit amplitude, is partially reflected at $x = 0$, such that transmitted and reflected waves are set up in the coal slab, and a plane wave is transmitted into the region beyond $x = \ell$. Satisfaction of the requirements of continuity of stress and particle velocity at the interfaces at $x = 0$ and $x = \ell$ allows one to compute the ratio of the amplitudes of the reflected wave (into the region $x < 0$) and the transmitted wave (into the region $x > \ell$) as

$$\frac{R_1}{T_3} = \frac{i}{2} \left(\frac{Z_B}{Z_C} - \frac{Z_C}{Z_B} \right) \sin(k_C \ell) \quad (6)$$

For the determination of the acoustic properties of coal samples, we propose to employ the above result in the system depicted in Fig. 2b. Two transducers are employed as sources of pulsed sinusoidal wave trains with

$$\hat{\sigma}_{inc,L} = A e^{ikx} ; \quad \hat{\sigma}_{inc,R} = B e^{-ikx} \quad (7)$$

in accordance with Eq. (3), with symbols L and R for left and right, respectively. The transducer at the left is to be used as a receiver and the complex amplitude of the signal it receives should be

$$\hat{\sigma}_{refl,L} + \hat{\sigma}_{trans,R} = (A R_1 + B T_3) e^{ik(2\ell-x)} \quad (8)$$

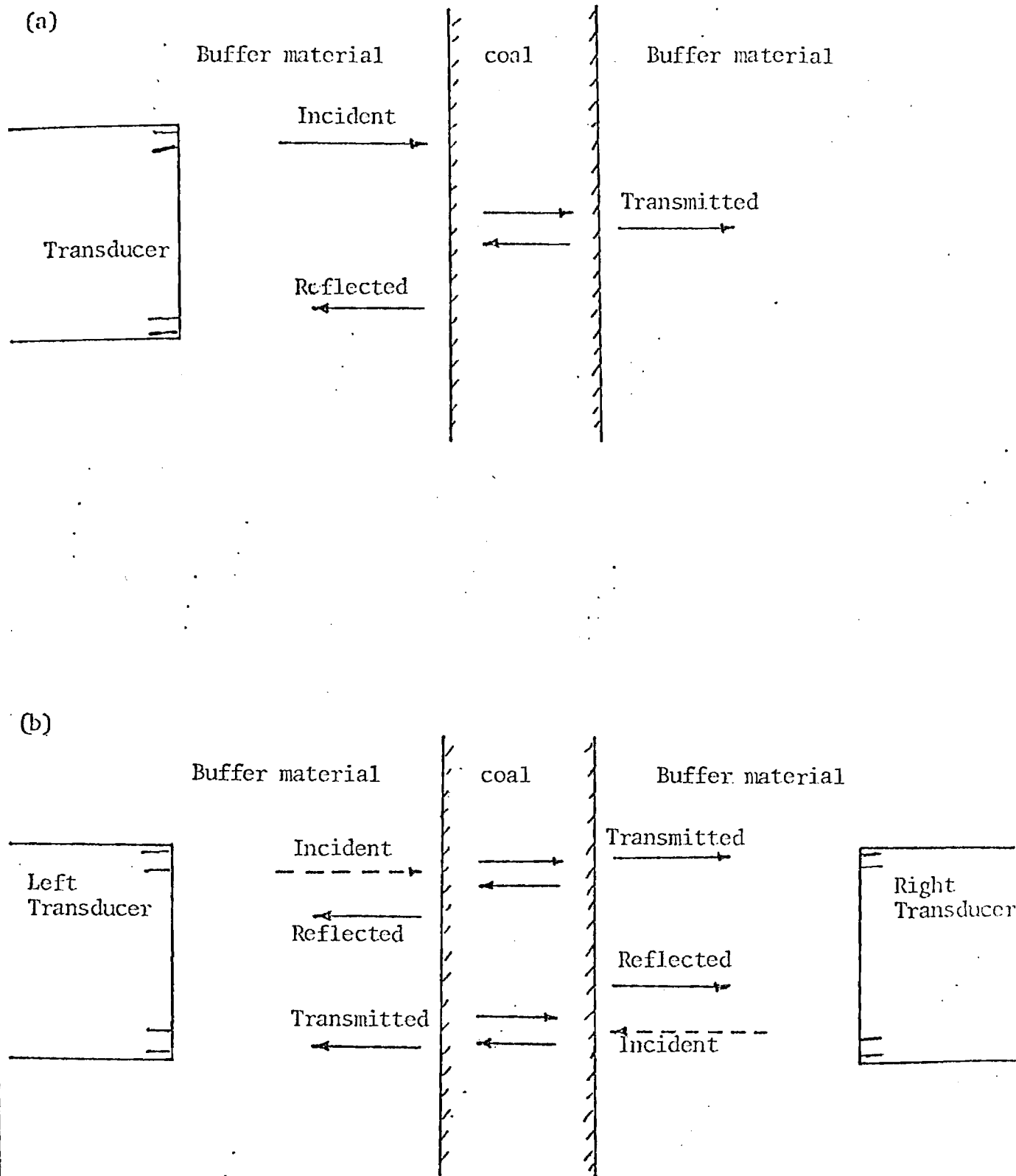


Figure 2. (a) Sketch of basic experimental model. An acoustic wave incident on a slab of coal surrounded by a buffer material gives rise to reflected and transmitted waves. (b) Wave confluence when two transducers, one on the left and the other on the right, simultaneously generate sound. The net wave received by the left transducer is the superposition of (i) a reflected wave originated by the left transducer and (ii) a transmitted wave originated by the right transducer.

If we adjust the relative amplitudes and phases of the waves emitted by the transducers so as to produce a null reading at the receiver, we must have

$$(V_R/V_L)_{\text{NULL}} = (B/A)_{\text{NULL}} \equiv G e^{-i\phi} = - (R_1/T_3) \quad (9)$$

with (R_1/T_3) given by Eq. (6). Given the gain G and the relative phase ϕ from voltages applied to the two transducers, one can then solve the transcendental equation

$$G e^{-i\phi} = - \frac{i}{2} \left(\frac{Z_B k_C}{\rho_C \omega} - \frac{\rho_C \omega}{Z_B k_C} \right) \sin(k_C \ell) \quad (10)$$

for the complex wavenumber k_C . The real part of k_C is the angular frequency divided by the phase velocity; the imaginary part is the attenuation coefficient.

Sample calculations of the gain factor G as a function of the quantity $k_I \ell$ (with k_I the imaginary part of k_C) are shown in Fig. 3. Here, for purposes of illustration, we have assumed the value unity for the parameter $X = \rho_C \omega \ell / Z_B$; curves of G vs. $k_I \ell$ are presented for several ratios of k_I to k_R (the real part of k_C). Similar plots of the phase angle ϕ vs. $k_R \ell$ are presented in Figure 4. From these two figures, we conclude that knowledge of the parameter X allows one to obtain values of k_R and k_I (and hence the phase speed and attenuation coefficient) without undue effort.

The primary sources of deviations in the experimental results from the above analytical results are: i) in the case of a solid buffer material, phase changes due to bonding of the transducers to the buffer rods and diffraction effects which arise because of the finite area of the transducers^{9,11}; ii) in case of a liquid buffer, diffraction of sound around the coal sample. In the

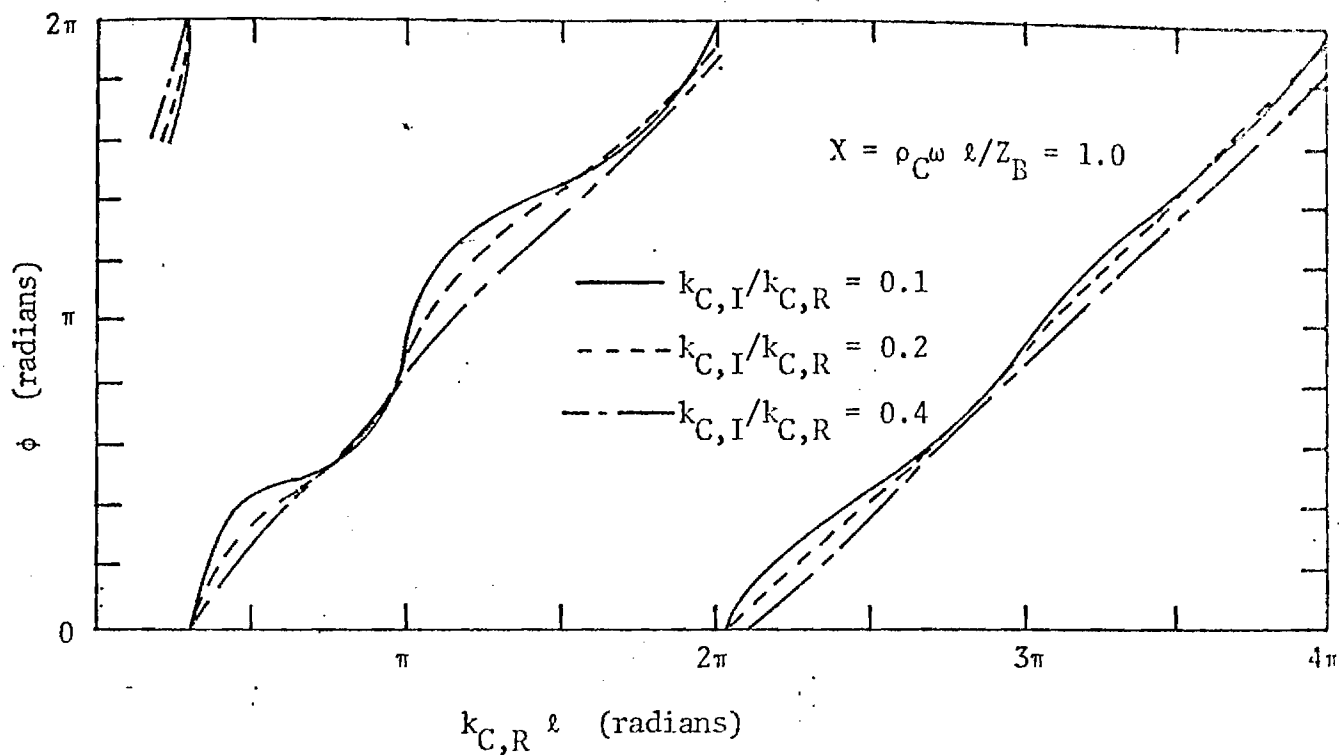


Figure 4. Some sample calculations of the phase angle ϕ versus the parameter $k_{C,R} l$. These curves for fixed $k_{C,I}/k_{R,I}$ supplement those of Fig. 5 and illustrate how one might determine k_R and k_I from a knowledge of the relative amplitudes and phases of the voltage inputs to the two transducers of Fig. 2b which are such that the net signal received by the left transducer is a null.

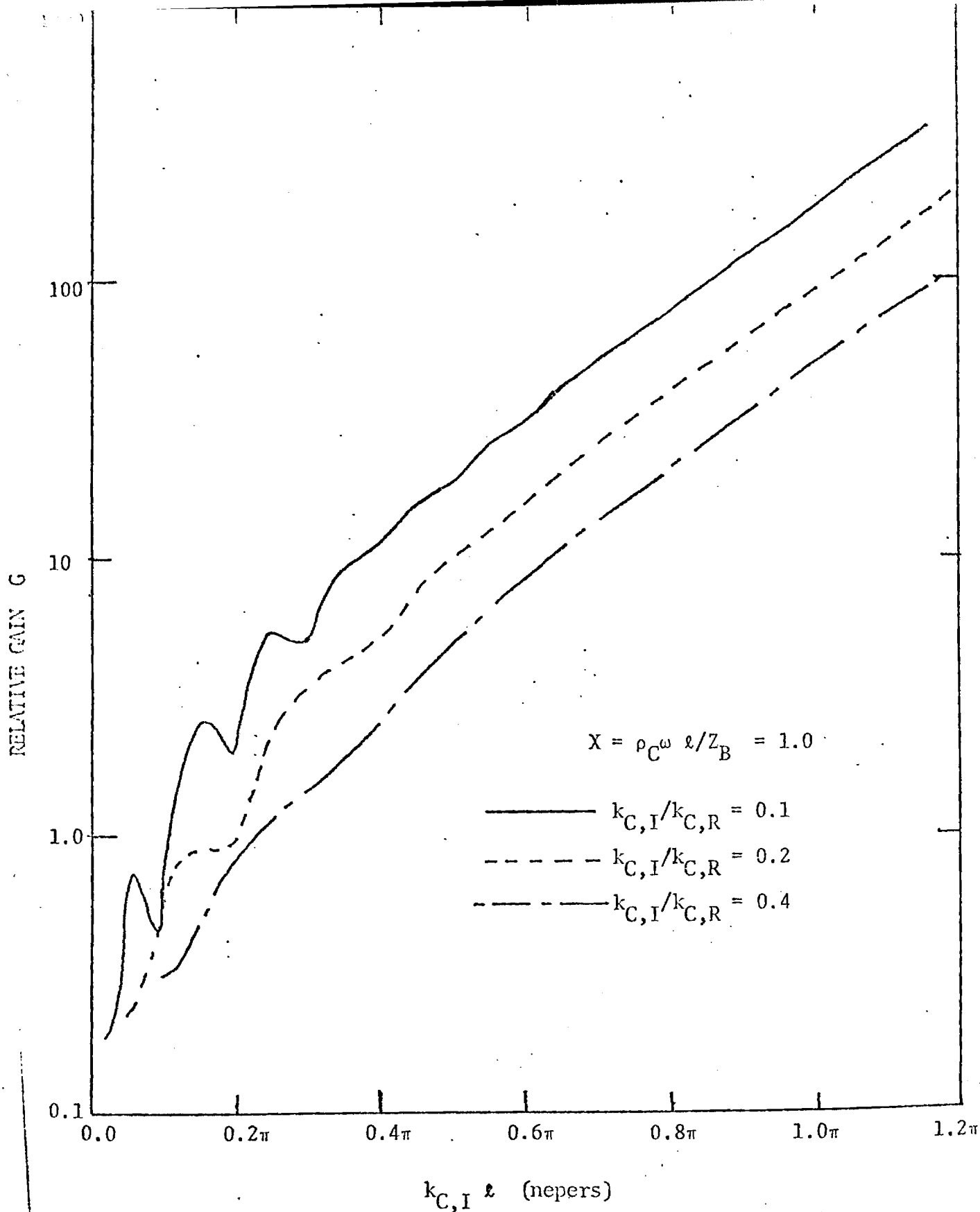


Figure 3. Some sample calculations of the relative gain G versus the quantity $k_{C,I} \ell$ for various fixed ratios of the imaginary part to the real part of the complex wave number k_C for propagation of constant frequency waves in coal.

latter case, we are confident that the use of a mask opaque to ultrasonic waves can be employed to hold the sample. For the solid buffer rods, we expect to develop extensions of previous corrections for the diffraction effects and to utilize the bond phase-shift corrections which have been obtained previously^{8,11,12}.

REVIEW OF INSTRUMENTATION

General Description

Instrumentation used to measure the acoustical properties of coal must be able to produce and receive two matched tone bursts at an adjustable relative time delay. The delay and signal amplitudes are then adjusted to achieve cancellation of the two bursts at the front face of the specimen. We propose to use a specially designed signal source to produce these excitation signals and conventional ultrasonic instrumentation to transmit, receive, and display the tone bursts and echos. Major components and general arrangement of the apparatus are shown in Figure 7. In order to operate successfully, phase and gain of the two signals must be independently adjustable. This requires that the response of each pair of transducers must be matched at the operating frequency. Likewise, the two corresponding R.F. amplifiers must have matched response from approximately 10KHz to 1 MHz.

Exploratory echo sounding studies will be done with single transducers and excitation signals. It is anticipated that reflections from the coal's back surface will be severely attenuated, so that specialized signal processing will be required to recover these signals. A digital oscilloscope will be used as a high-speed digitizing recorder and will be directly interfaced to a digital computer for on-line and remote signal processing. This is illustrated in Figure 8. Suitable digital computers are available within the School of Mechanical Engineering. The necessary digitizing of the acoustic signal, amplification, display and digital storage and recovery can be provided by the oscilloscope specified below. In addition, suitable interfacing between the oscilloscope and the computer may be required.

Tentatively, we plan to use the same transducers for measurement of acoustic properties and for echo sounding, but it may be necessary to obtain highly damped transducers for the latter part of the experiments. Should the need arise for transducers with different characteristics than those on hand or available we may attempt to modify the existing transducers to enhance their damping.

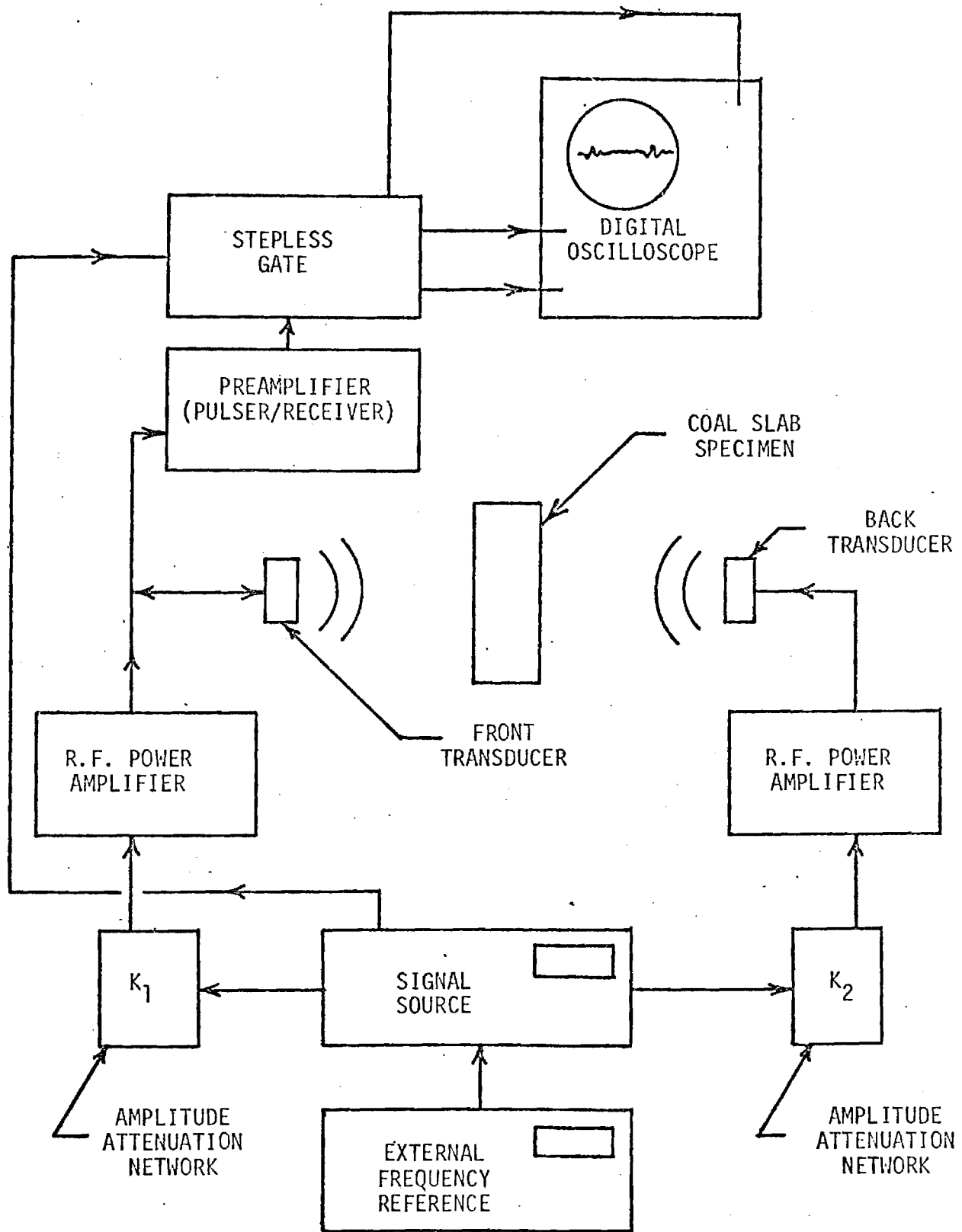


Figure 7. Apparatus to measure the acoustic properties of coal.

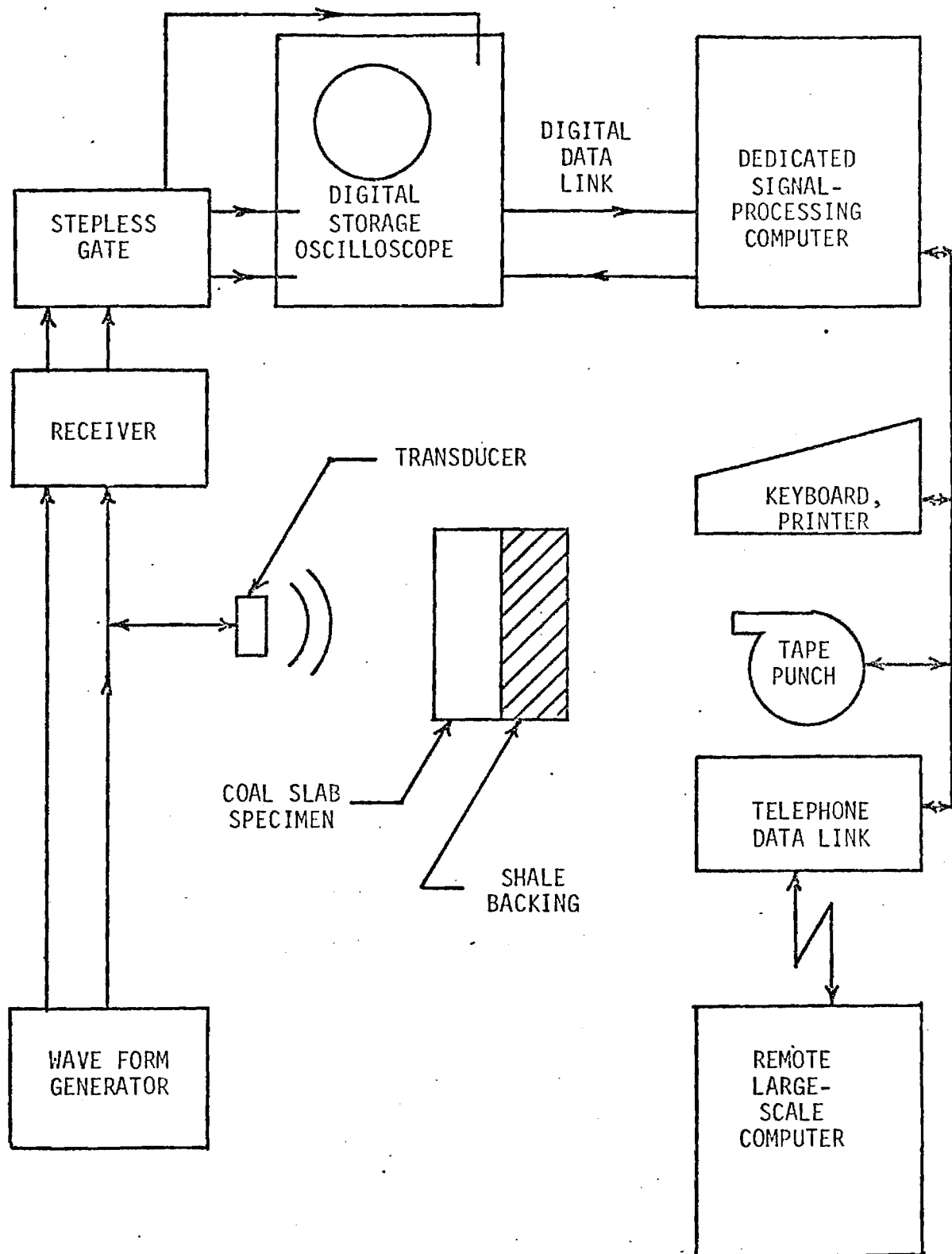
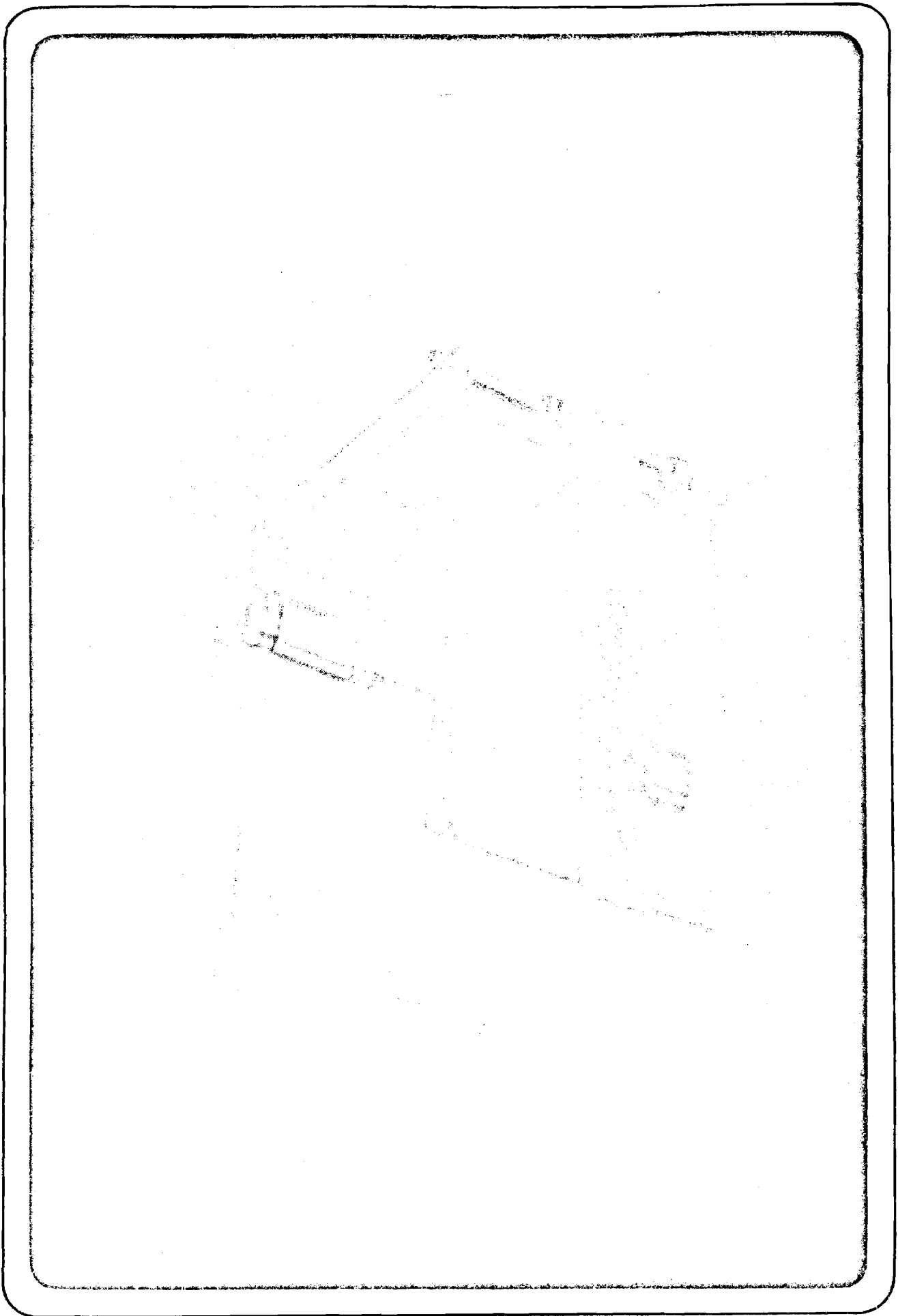


Figure 8. Apparatus for exploratory sounding experiments for the development of a system of measuring coal slab thicknesses.



Precise Control of the Relative Phases of Two Ultrasonic Pulses using Digital Logic Circuitry, John M. Mills and Thomas H. Carolus, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

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. Any integer number of sinusoidal cycles, from one to nine cycles, are generated as a burst. A delay counter is started coincident with the sinusoidal waveform generator. Upon completion of this preset delay interval a second sine counter 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 pulses can be delayed by any integer multiple of 1/10-th of a period of one sinusoid. The three-decade delay counter allows the total delay between the two pulses to be as much as 100 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.

Technical Committee: Engineering Acoustics
Subject Classification Number(s):
Telephone Number: (404) 894-3259
Special facilities: None

V-1000

The Acoustic Properties of Coal, H. Joseph Venne, Jr., School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332

A survey of recent literature reveals sizable discrepancies in quoted values for the wave speed in coal; quoted values range from 1.2×10^3 m/sec to 2.3×10^3 m/sec. Negligible data exist for the values of the attenuation in coal. Present paper discusses design and execution of experiments (still in progress) to determine these properties. A coal slab is immersed in water between matched transducers. Both emit pulses, but their relative phases and amplitudes are externally controlled. The amplitude and phase of the right transducer is adjusted until the received pulse at the left transducer is a null. The received pulse consists of sound from the right transducer transmitted through the slab, plus sound from the left transducer reflected from the slab. The technique is a modification of that developed by McSkimin [J. Acous. Soc. Amer. 23, 429-434 (1951)]. The gain factor G times $\exp(i\phi)$, where ϕ is relative phases of the two incident pulses, is shown to be a transcendental function of the complex wave number. Simultaneous graphical solution of the real and imaginary parts of this equation yields the sound speed and the attenuation. Results obtained using this technique are discussed. [Work supported by NASA]

Technical Committee: Physical Acoustics
Subject Classification number(s): 43.35.Bf
Telephone number: (404) 894-3259
Special facilities: None

On Acoustic Echo Measurements of Thicknesses of Slabs of Dissipative Materials,
Chew, Chye Heng, School of Mechanical Engineering, Georgia Institute of
Technology, Atlanta, GA 30332

Present paper discusses some exploratory experiments and analytical studies directed towards the development of an acoustic sensing system for the monitoring of remaining coal slab thicknesses during longwall mining. The prototype system envisioned uses water as a coupling medium; reflected echoes resulting from a transducer excited incident pulse will come from the water-coal interface and from the coal-shale interface. A principal difficulty is the high attenuation in coal; exploratory experiments suggest it to be of the order of 2 Nepers/wavelength. If this is the case, then the tail of the water-coal interface echo (which is received first) may mask the echo from the coal-shale interface. A brief theoretical analysis indicates that this masking will not occur, regardless of the thickness of the slab, if the Q of the transducer is less than $\pi / \alpha \lambda$. If $\alpha \lambda$ is 2, then a relatively low Q is required. However, the second echo may possibly still be extracted, even if masking occurs, if a small parameter model of the transducer and of the coal slab is adopted. The early return of the echo can be extrapolated to determine what the echo would be were the coal slab of infinite thickness; subtraction of this from the total echo yields the echo from the shale interface. [Work supported by NASA]

Technical Committee: Engineering Acoustics
Subject Classification number(s): 43.85.Bh, 43.88.Ar
Telephone Number: (404) 894-3259
Special Facilities: None

GEORGIA INSTITUTE OF TECHNOLOGY
School of Mechanical Engineering

Applications of Acoustics in the
Measurement of Coal Slab
Thickness

Monthly Progress Report No. 7
for the period
March 1, 1979 through March 31, 1979

Contract No. NAS8-33093

Prepared for:
George C. Marshall Space Flight Center
Marshall Space Flight Center
Alabama

Prepared by:
W. James Hadden, Jr.
Co-Investigator

March 28, 1979

Re: Applications of Acoustics in the Measurement of Coal Slab Thickness
Contract No. NAS8-33093

Item: Progress Report No. 7

Date: March 28, 1979

PROGRESS TO DATE

This report covers the period February 1, 1979 to February 28, 1979. Most of the progress made during this period is summarized in Progress Report No. 6 which was issued on February 14, 1979. The present report consists of a copy of a Summary-Briefing of the overall progress made on the project. It includes in particular the detailed diagrams of the circuitry which has been constructed for the experiments on the acoustics properties of coal.

Figure 1. Photograph of test cell designed and constructed for Georgia Tech experiments on the acoustic properties of coal. An aluminum mounting plate (thickness $\frac{1}{4}$ inch) holds the sample and prevents diffracted sound from reaching the receiving transducer. During operation, the cell is filled with water, the sample is mounted in the hole in the plate. Two matched transducers are mounted on opposite sides of the cell. The design is such that the position of the sample between the two transducers can be varied.

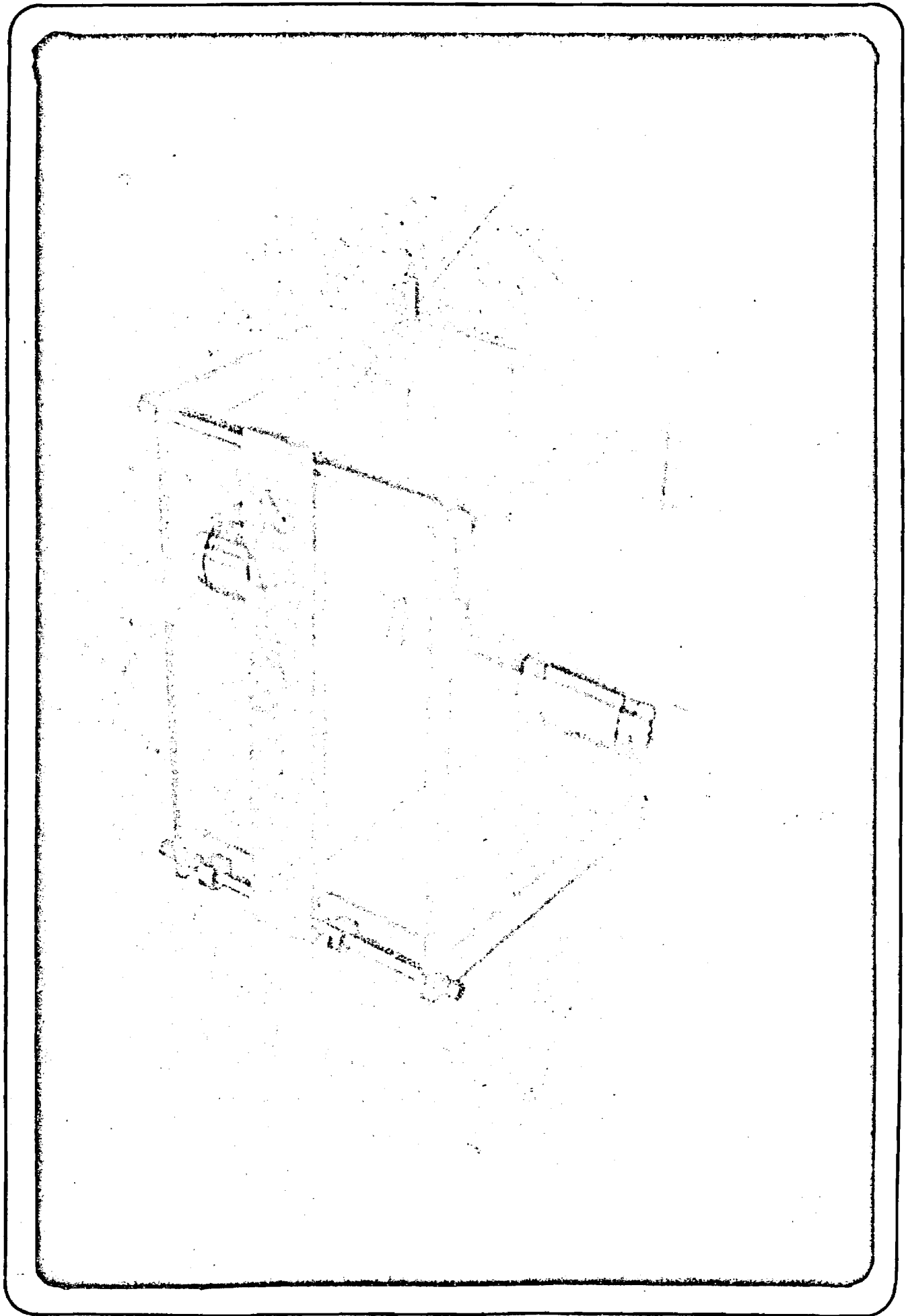
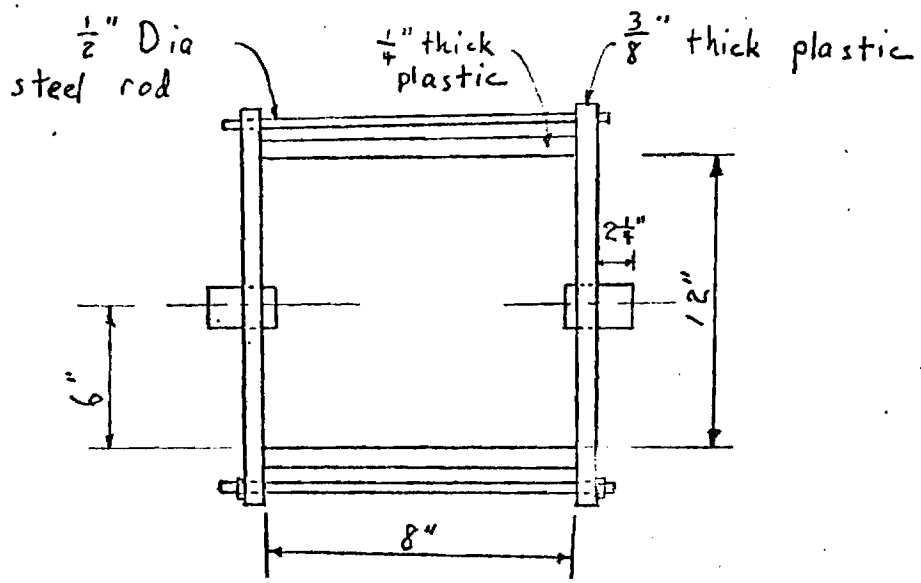
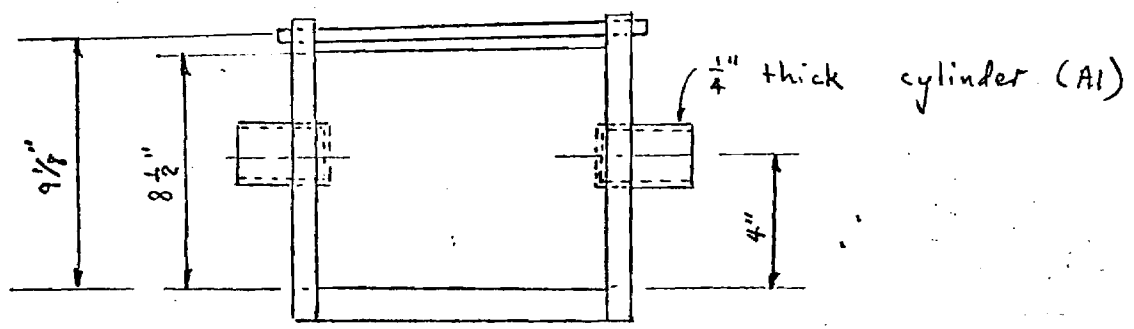


Figure 2. Detail design sketches of test cell shown in Fig. 1.

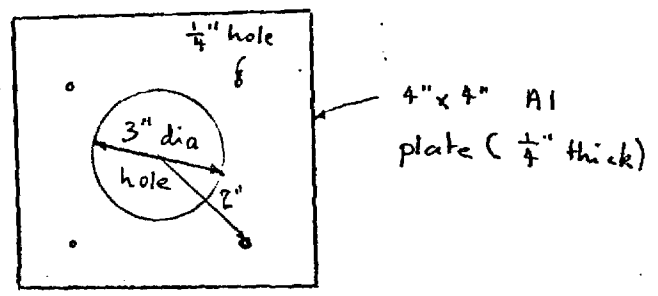
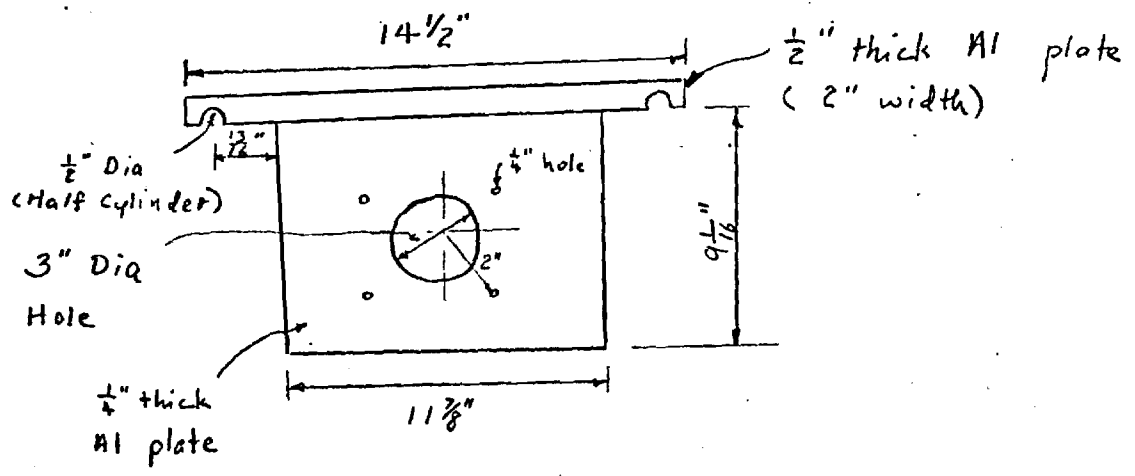


PLAN

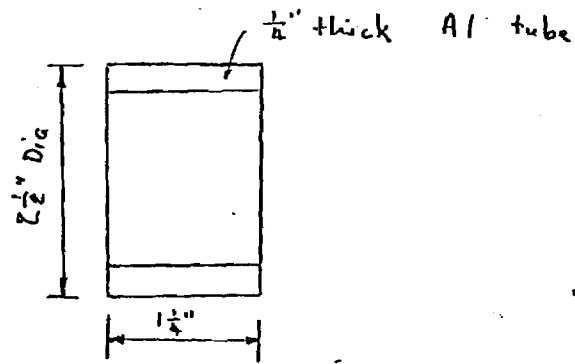
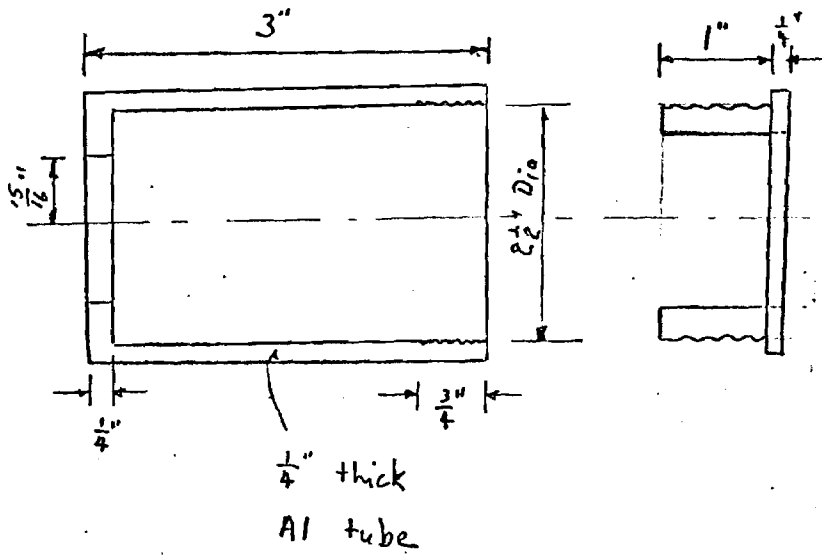


ELEVATION

TEST CELL

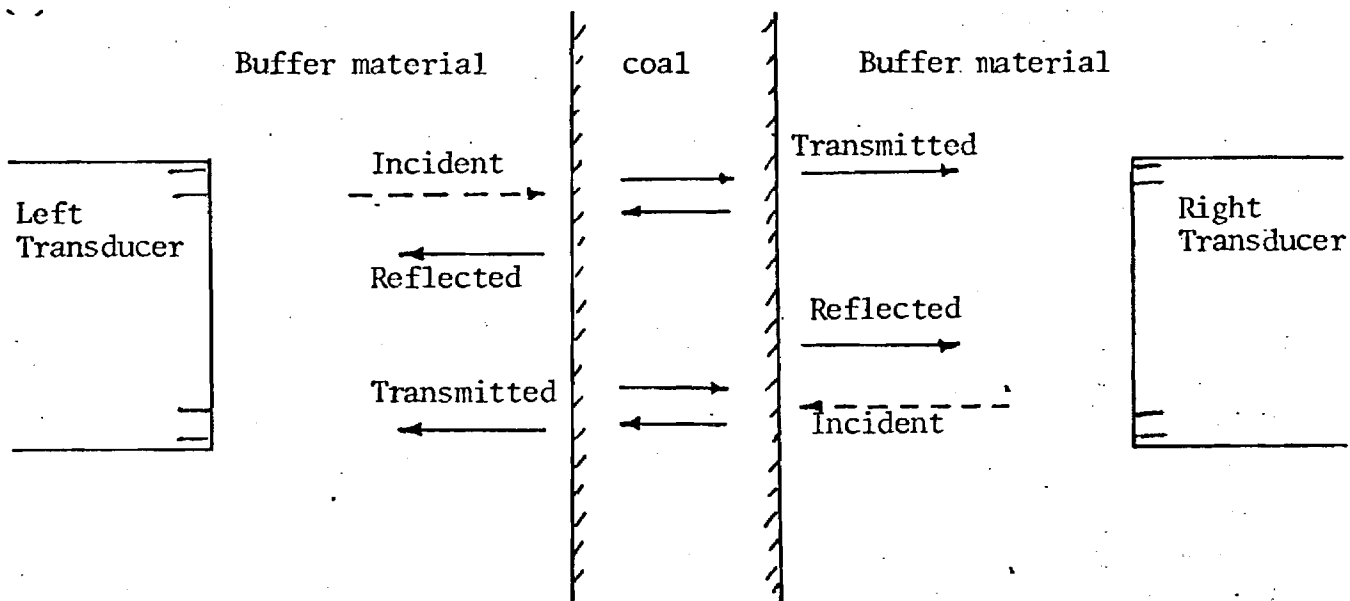


MOUNTING PLATE



HOLDER FOR TRANSDUCER

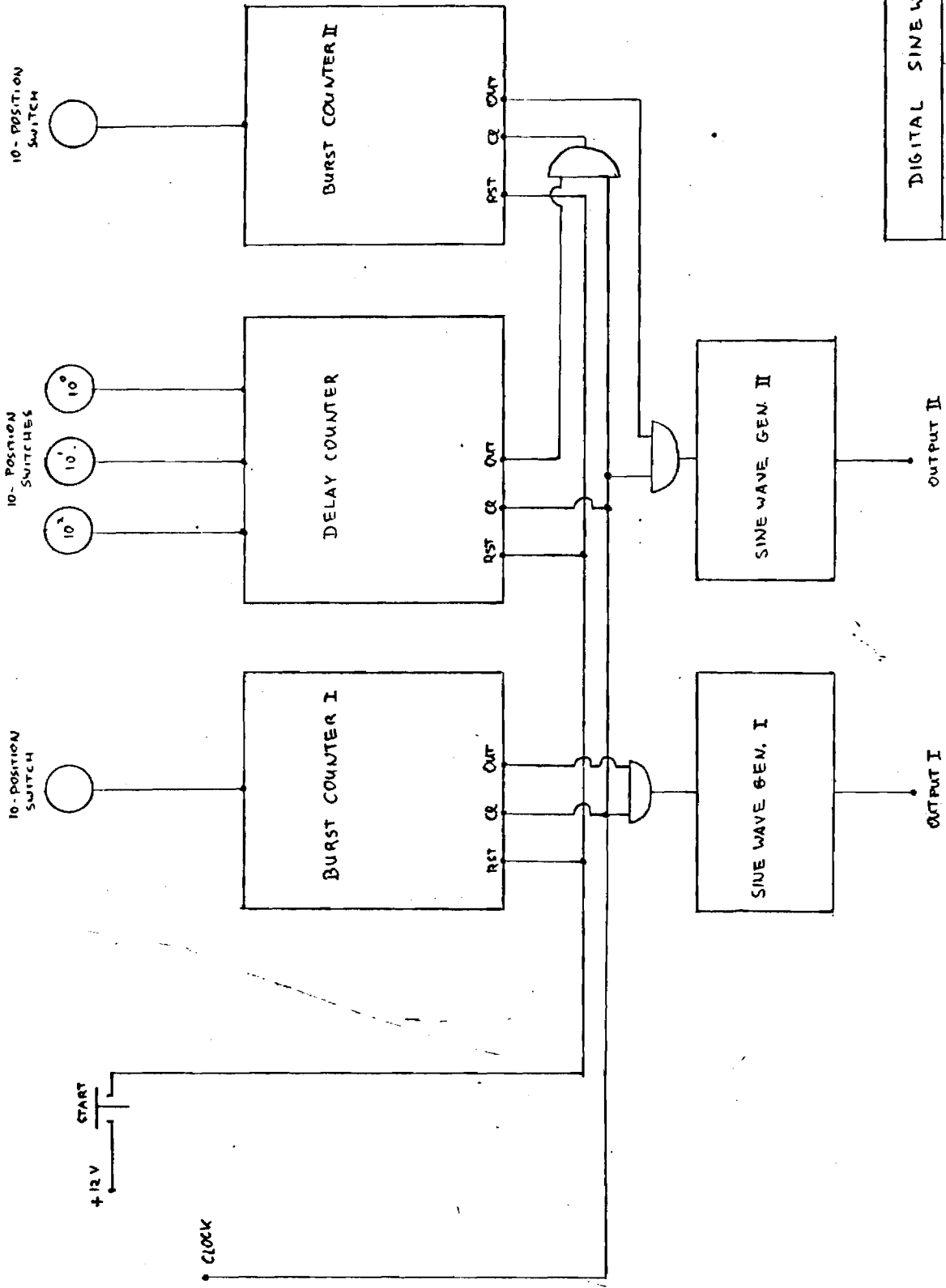
Figure 3. Basic experimental concept. The left transducer and right transducer generate precisely controlled pulses with variable phase delays which are reflected and transmitted by the intervening coal slab. The measurement consists of the relative gain and phase delays of the two transducers such that the net received pulse at the left transducer is a null.



$$G e^{-i\phi} = -\frac{i}{2} \left(\frac{Z_B k_C}{\rho_C \omega} - \frac{\rho_C \omega}{Z_B k_C} \right) \sin(k_C \ell)$$

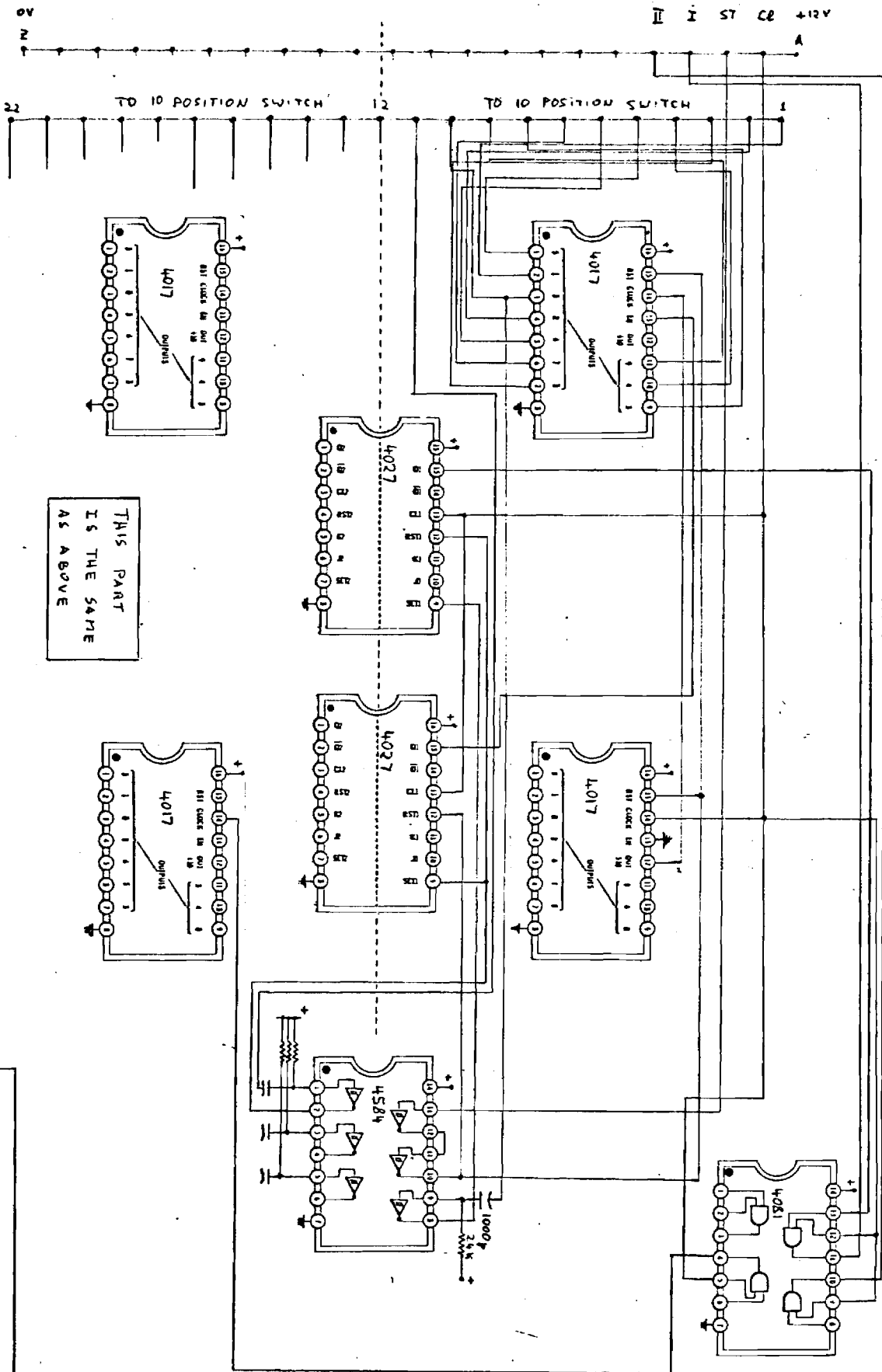
Figure 5. Basic transcendental equation, whose solution, given the gain G and relative phase ϕ of the two transducer voltages, allows the solution for the sound speed and attenuations in coal.

Figure 4a. Block diagram of the digital sine wave generator for controlling relative phases and pulse durations of voltages input to the two transducers. This has been designed and fabricated during the Georgia Tech project.



DIGITAL SINE WAVE GENERATOR
MILLS/CAROLUS
BLOCK DIAGRAM

Figure 4b. Detailed circuit diagram of the burst counters which are an essential part of the device whose block diagram is given in Fig. 4a.



BURST COUNTERS
MILLS / CAROLUS
CIRCUIT DIAGRAM

Final Report

**APPLICATIONS OF ACOUSTICS IN THE
MEASUREMENT OF COAL SLAB THICKNESS**

By

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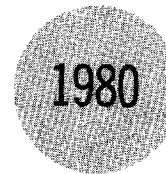
National Aeronautics and Space Administration

George C. Marshall Space Flight Center

NASA Contract No. NAS8-33093

29 February 1980

GEORGIA INSTITUTE OF TECHNOLOGY
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OF COAL SLAB THICKNESSES

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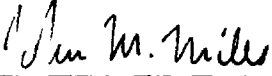
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Research Sponsored
by
National Aeronautics and Space Administration
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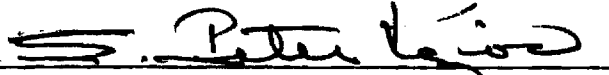

S. Peter Kezios, Director
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Chapter I

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 attenuation rate in coal at ultrasonic frequencies; development of analytical techniques for interpreting the data from both the exploratory experiments and projected

¹P. 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 attenuation 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:

¹H. 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;

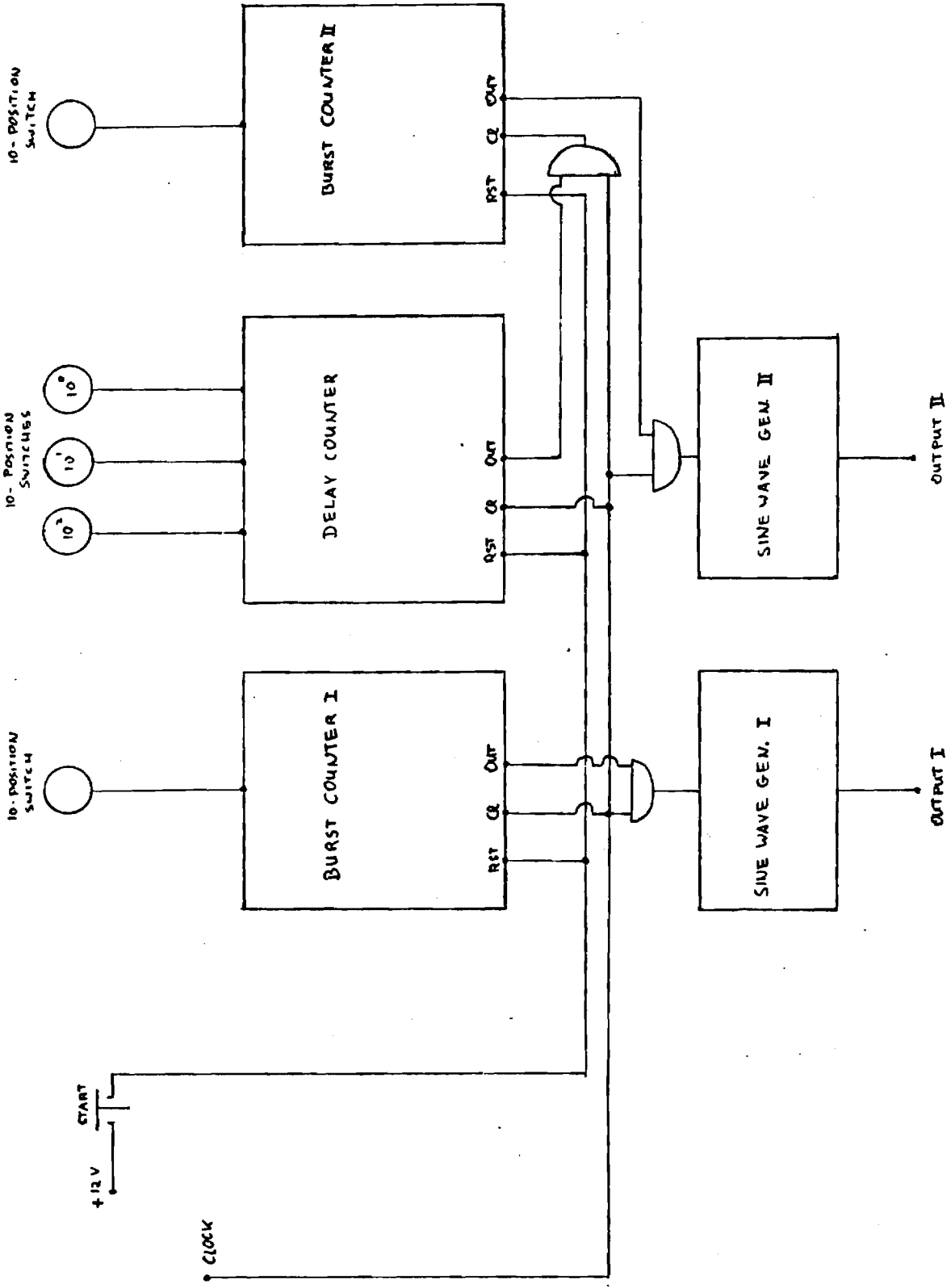


Figure 2.1. Digital Sine Wave Generator

- 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

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

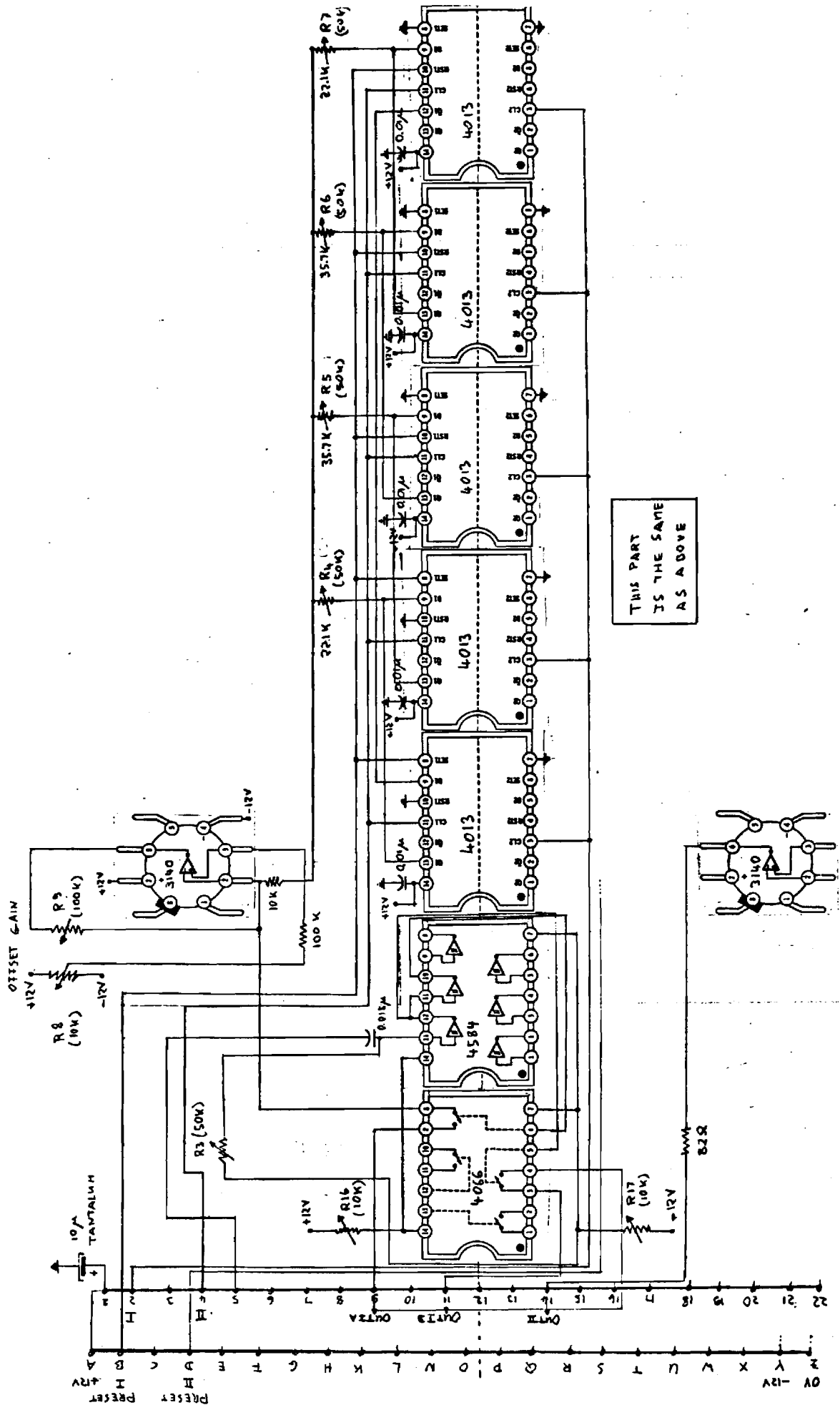


Figure 2.2. Sine Wave Generators with Amplifiers and Gates

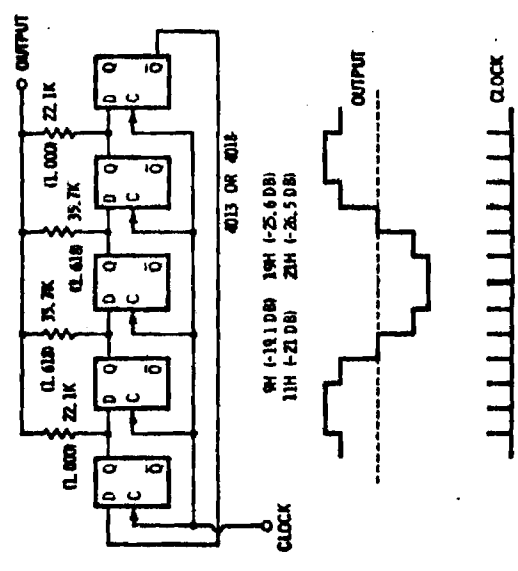
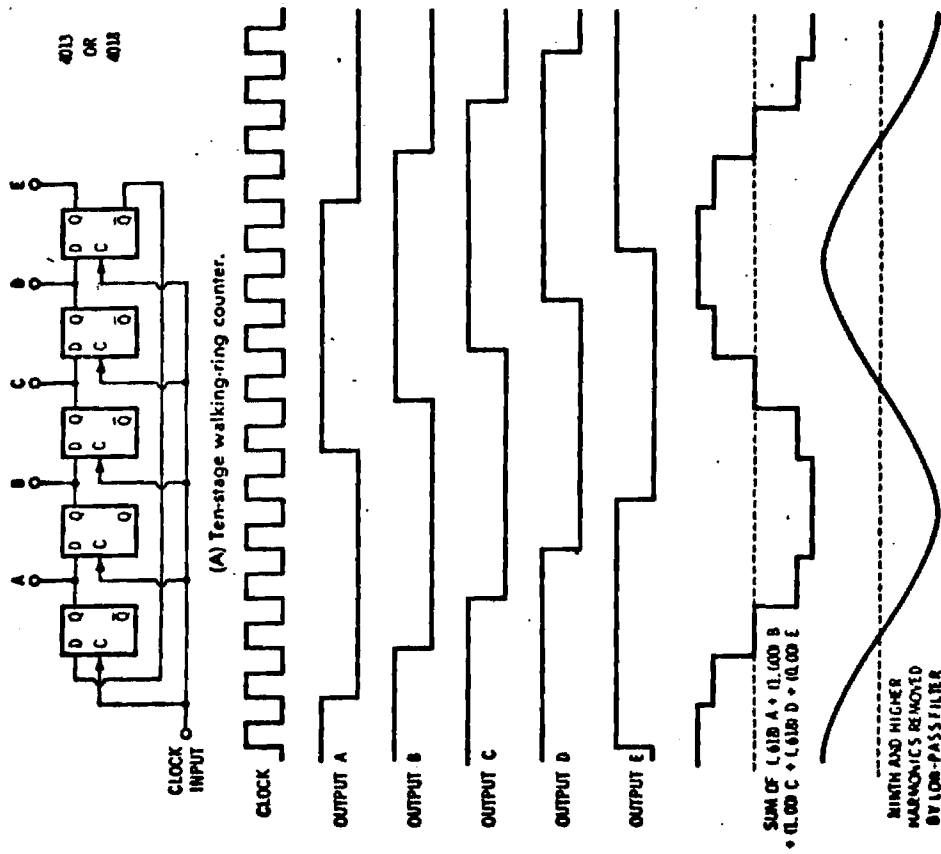


Figure 2.3b. Five-stage Generator (CMOS Cookbook)

Figure 2.3a. Converting a Walking-ring Counter into a Digital Sine Wave 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.

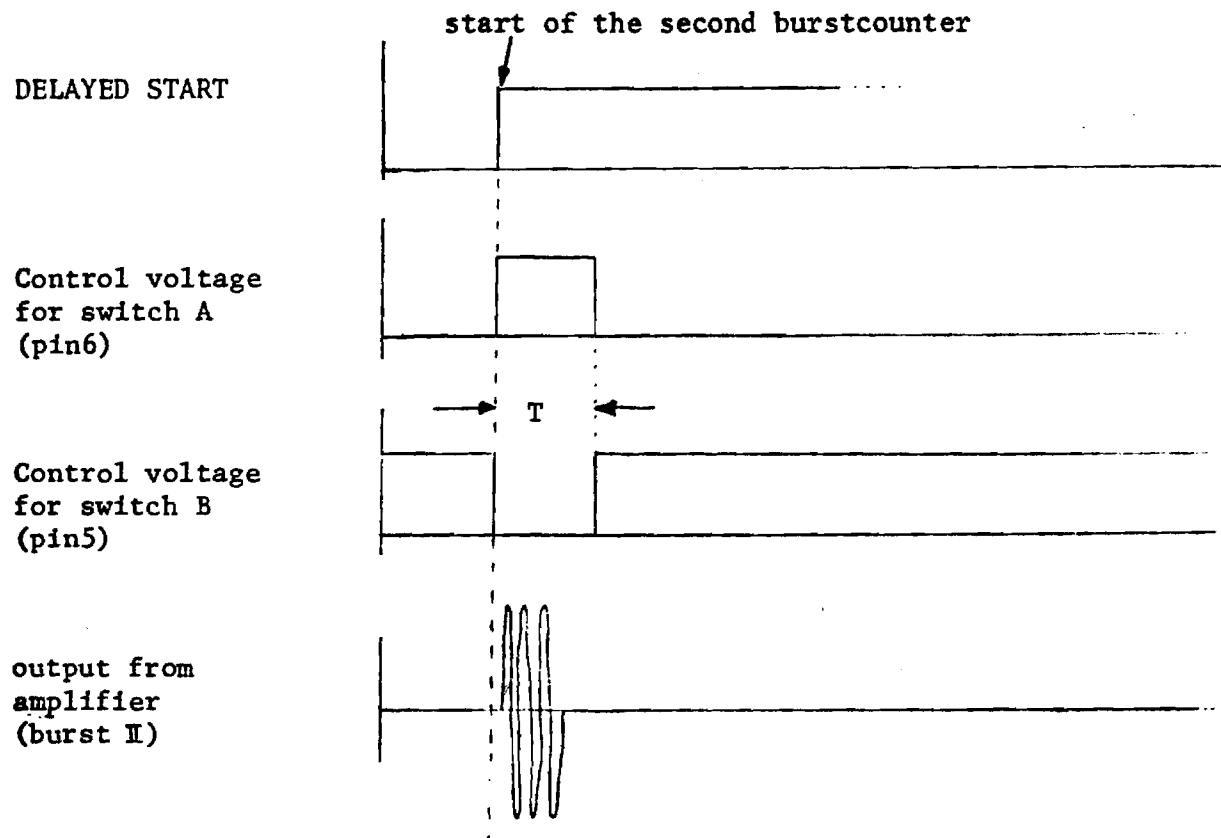


Figure 2.4. Pulse Diagram

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

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

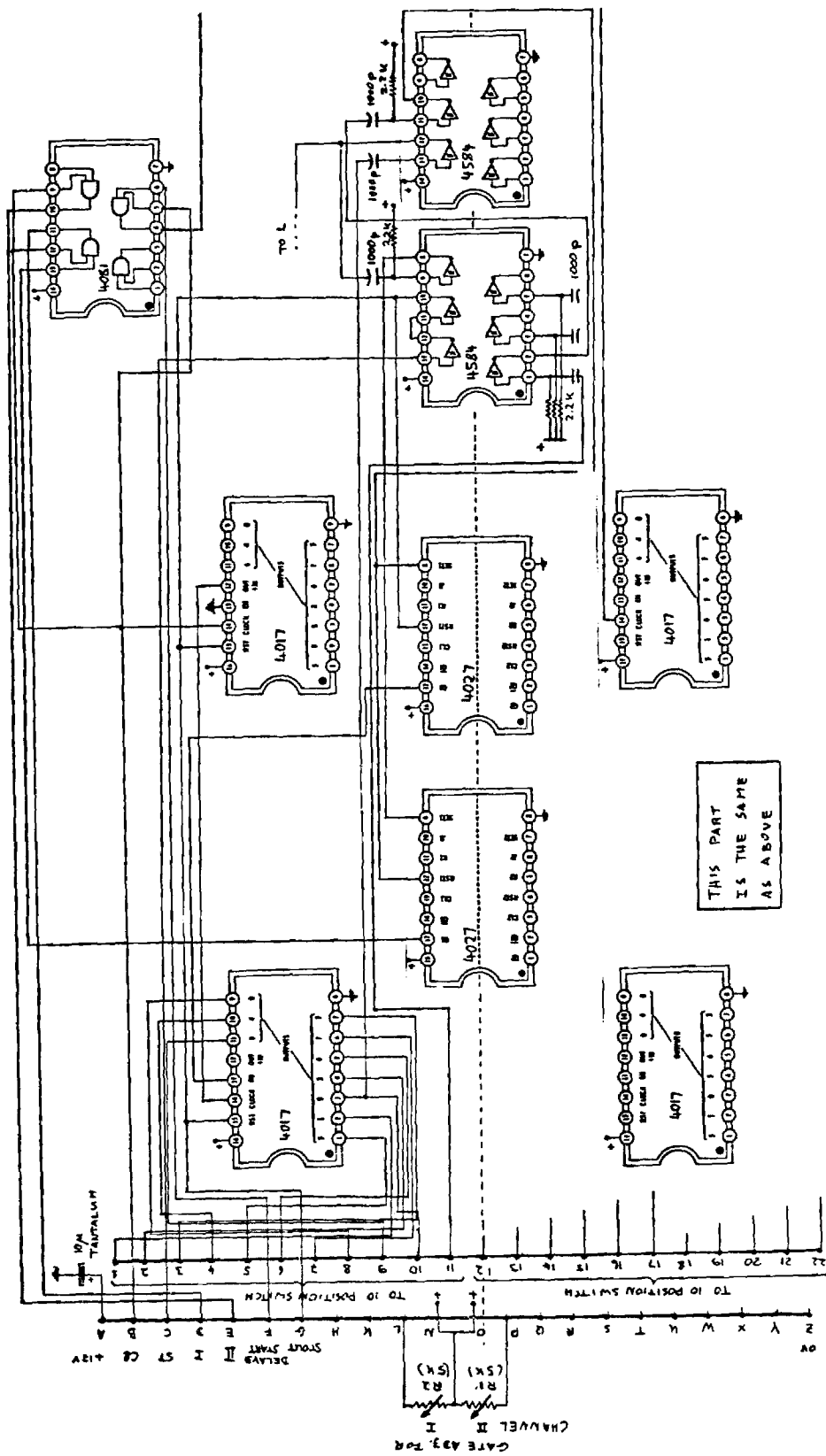


Figure 2.5. Burst Counters

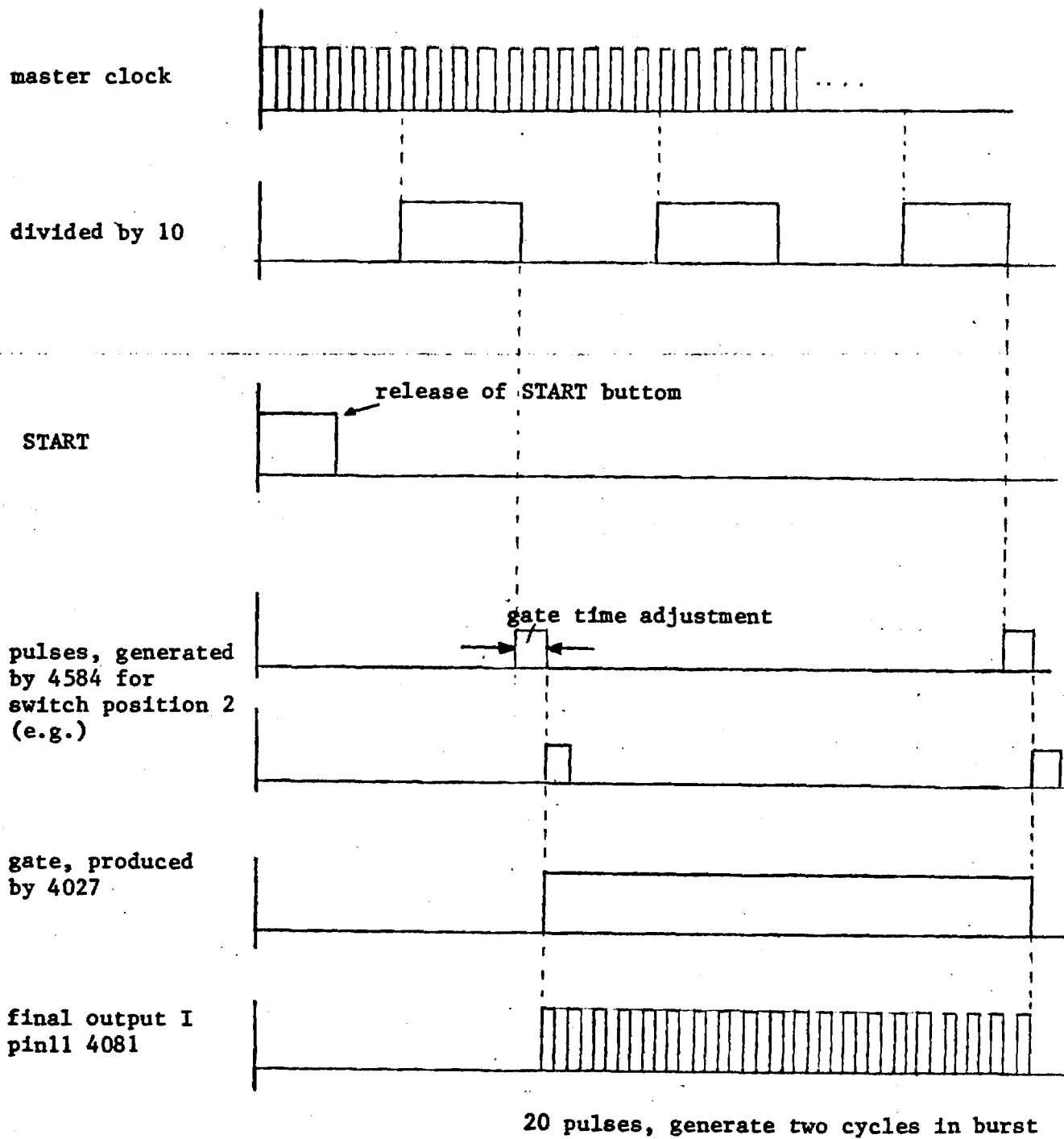


Figure 2.6. Pulse Diagram

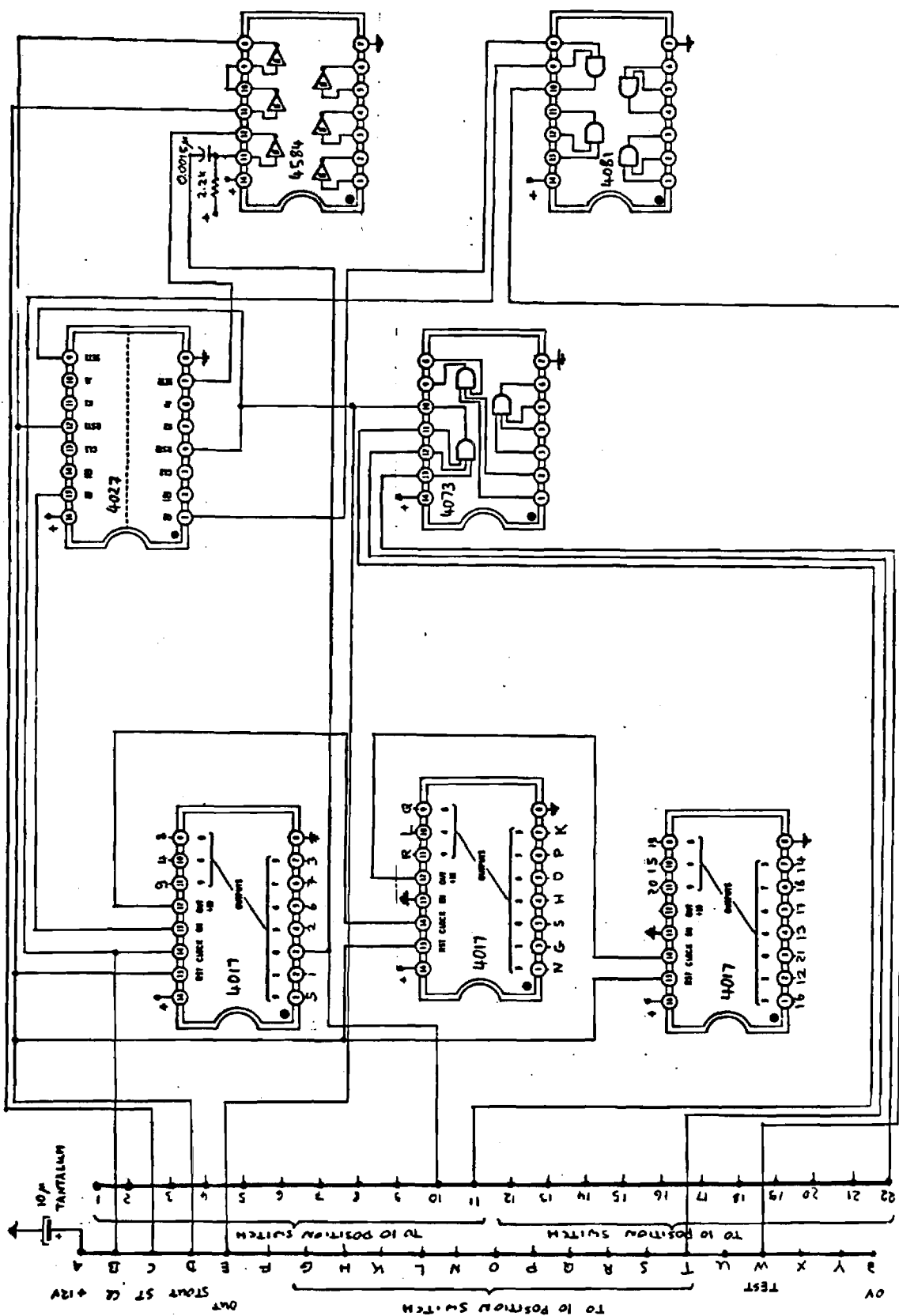


Figure 2.7. Delay Counter

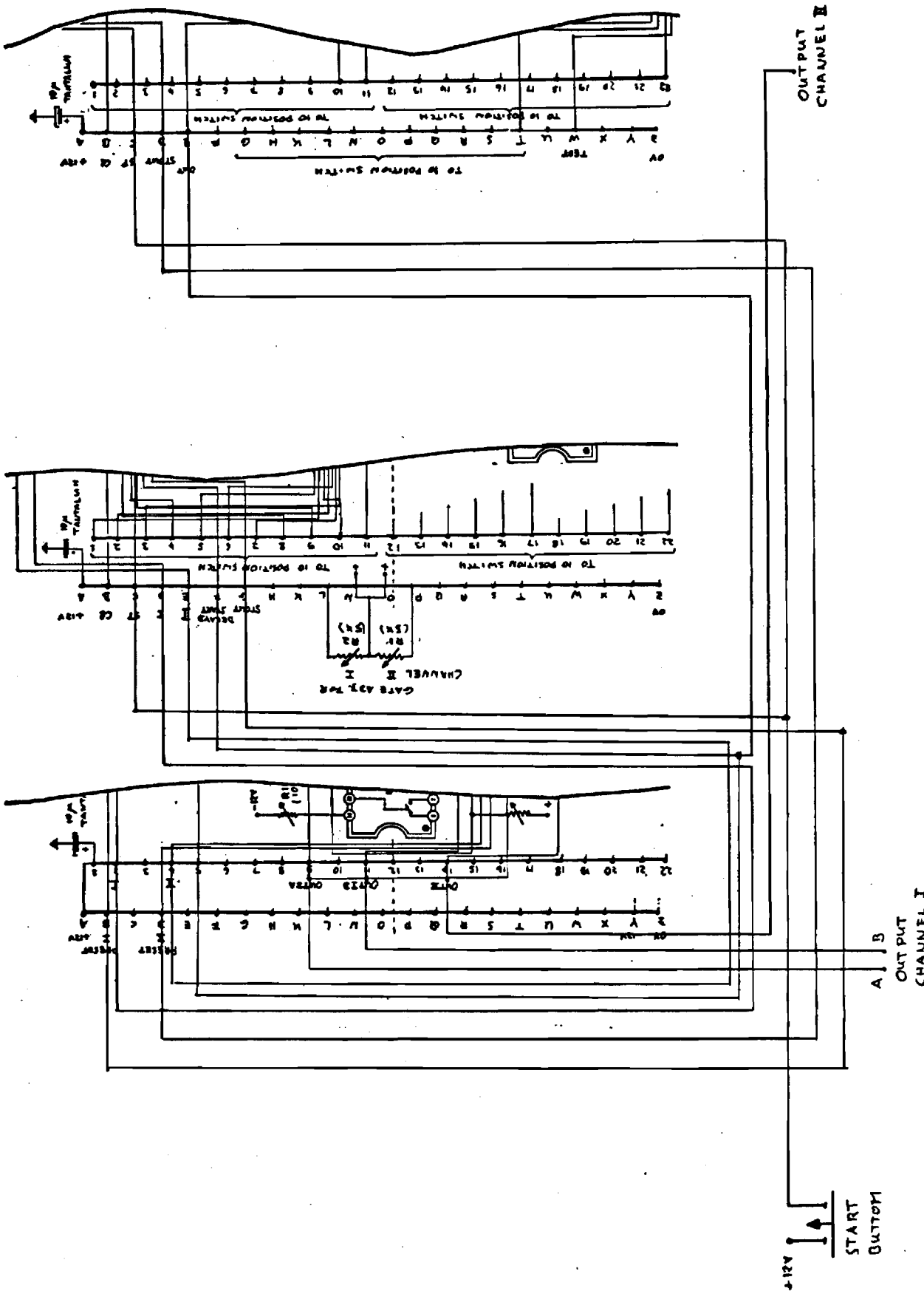


Figure 2.8. Connection of the Board

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.

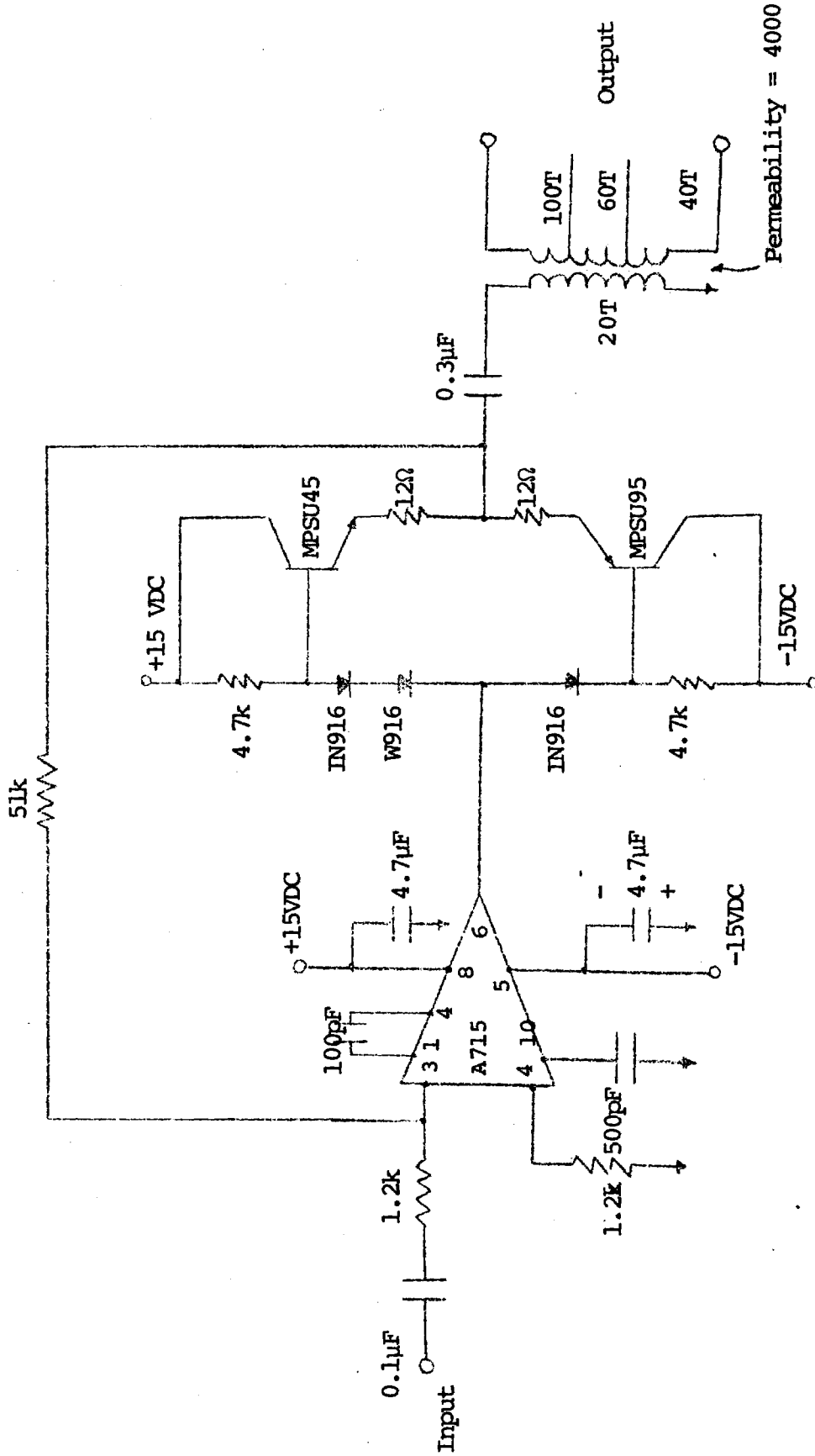


Figure 2.10. Schematic Diagram of Buffer Amplifier and Transformer.

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 μ s can be generated¹ 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.

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

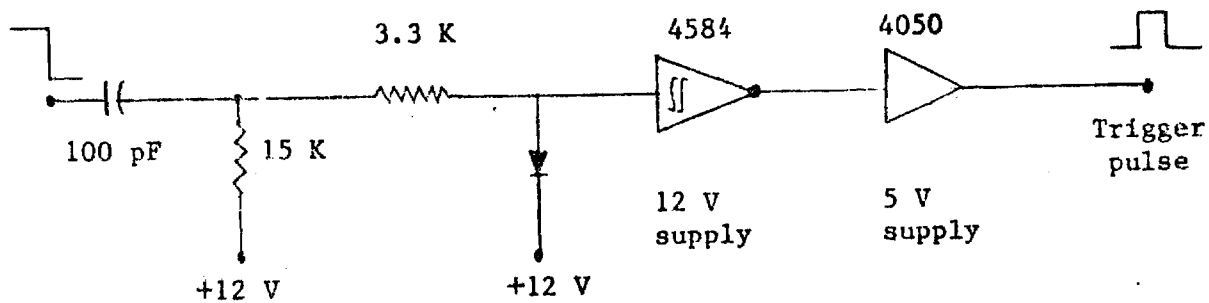


Figure 2.11. Stepless Gate.

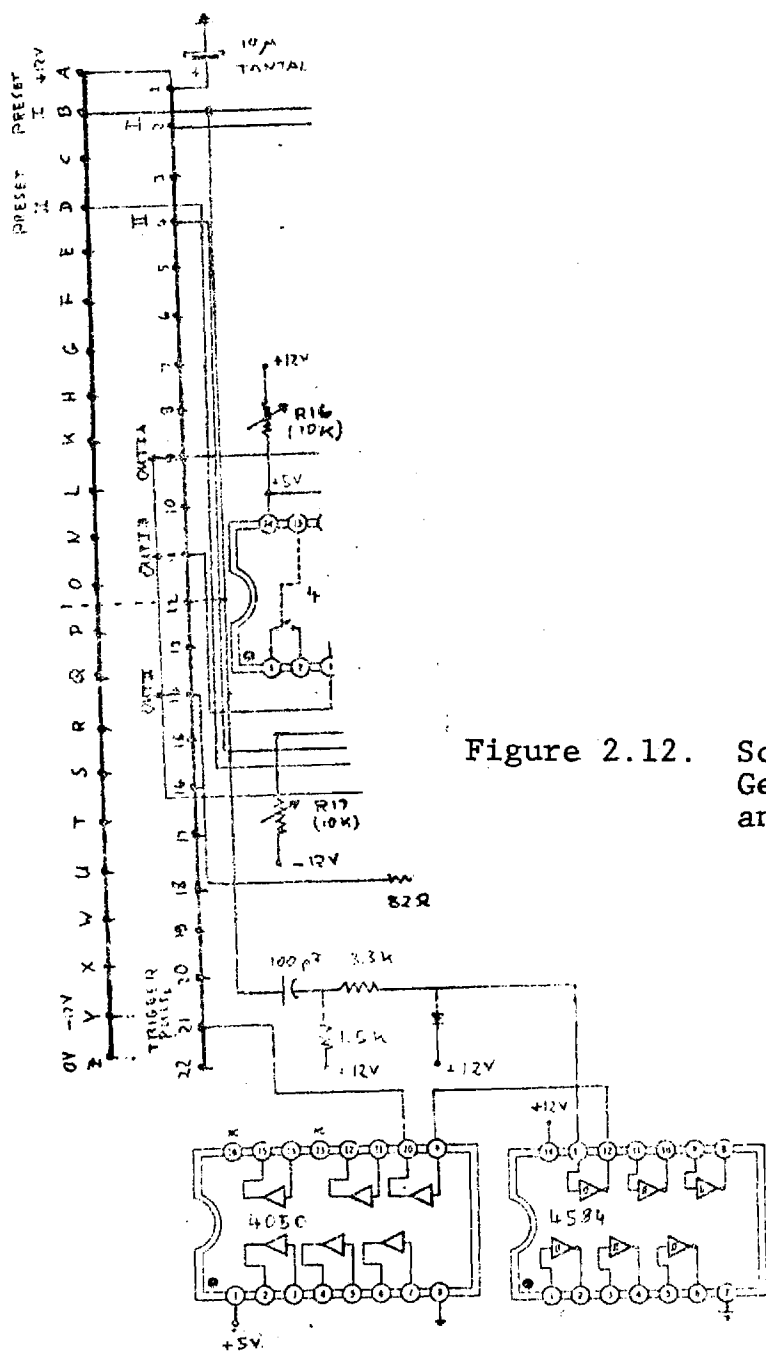


Figure 2.12. Schematic of Sine Wave Generators with Amplifiers and Gates.

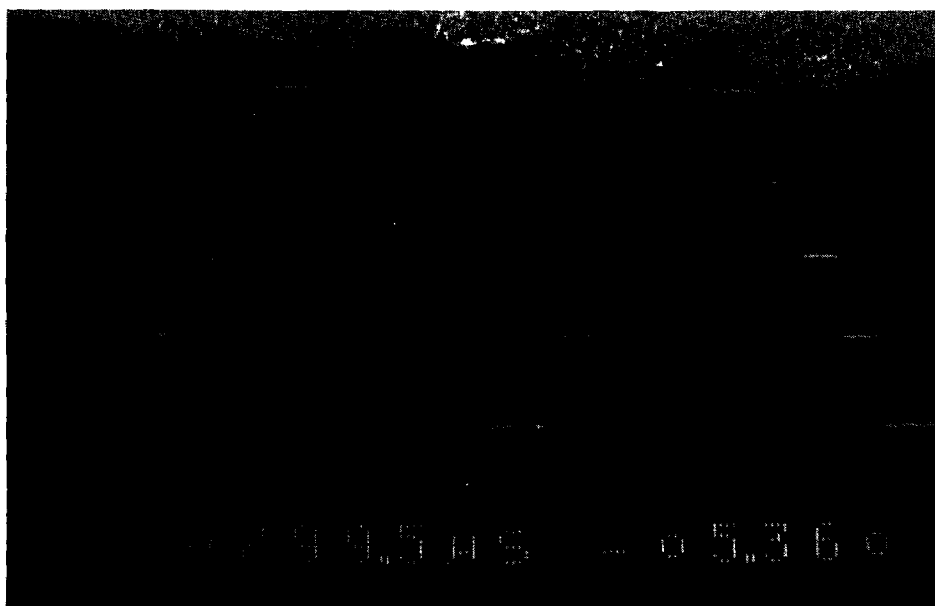


Figure 2.13. Two Cycles of a 10 kHz Burst

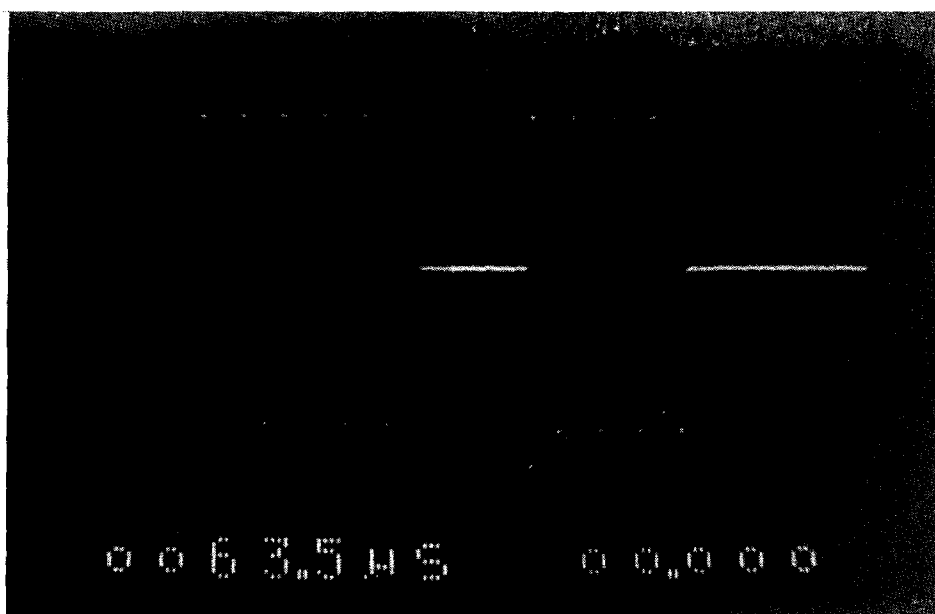


Figure 2.14. Two Bursts, the First with Six Cycles, the Second (delayed) with Four Cycles

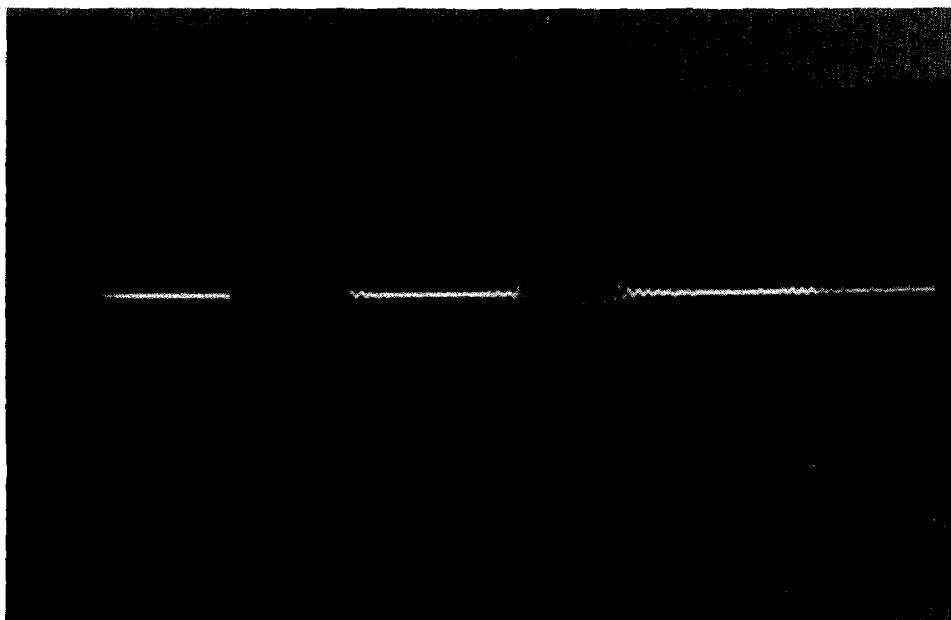


Figure 2.15. Transmitted Burst and Subsequent Echoes

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.

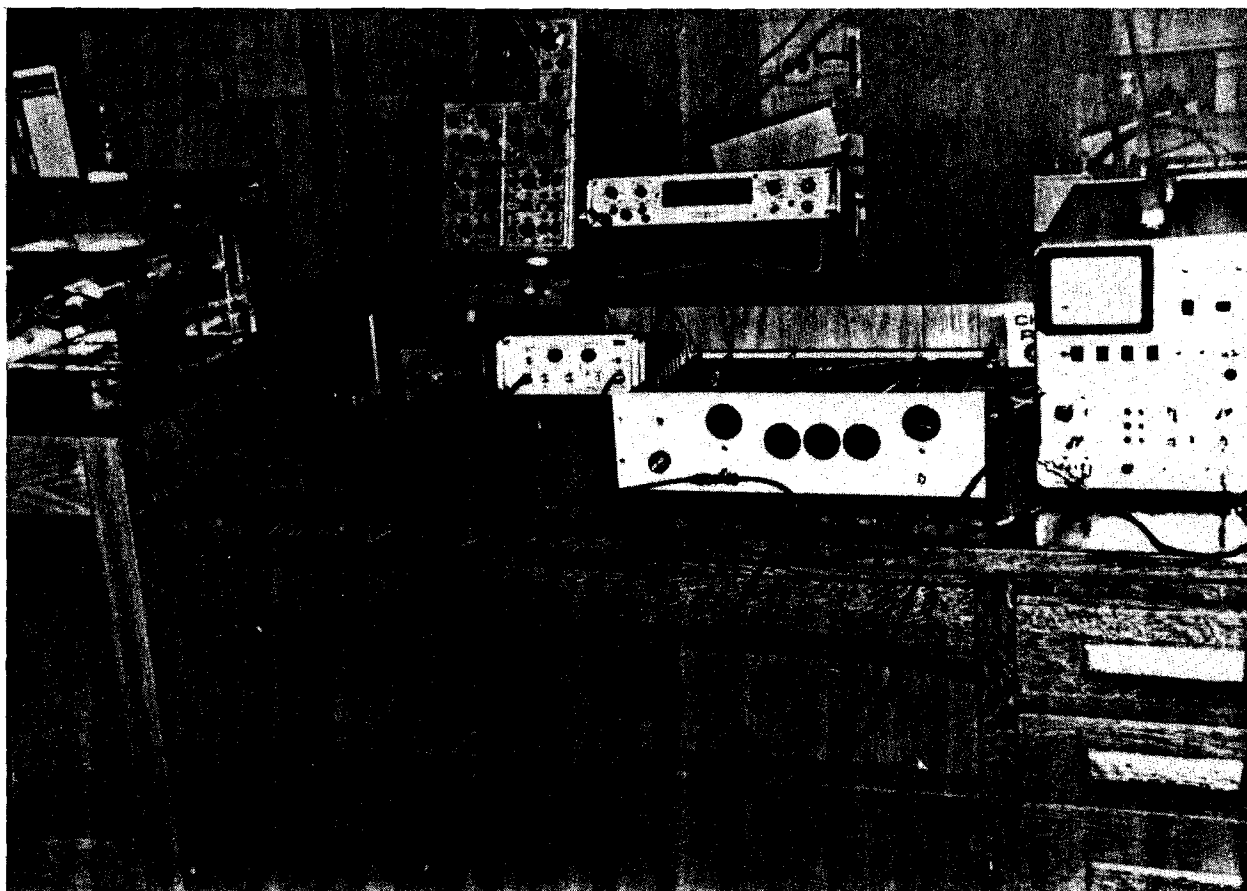


Figure 2.16. Layout of the Experimental System (Water Tank, Amplifier, Sine Wave Generator, Digital Oscilloscope).

clock sine wave burst counters delay counters
 | | | |
 | | | |

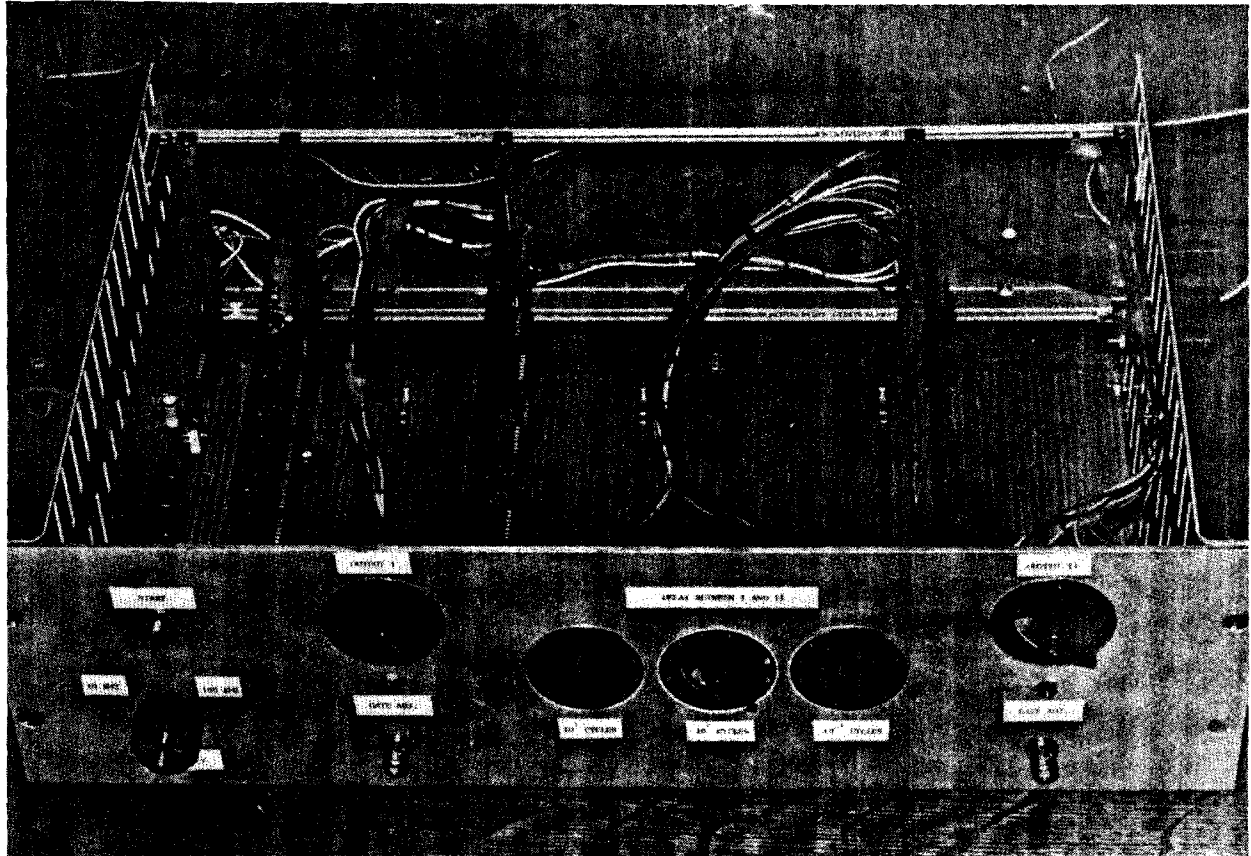


Figure 2.17. Top View of Digital Sine Wave Generator.

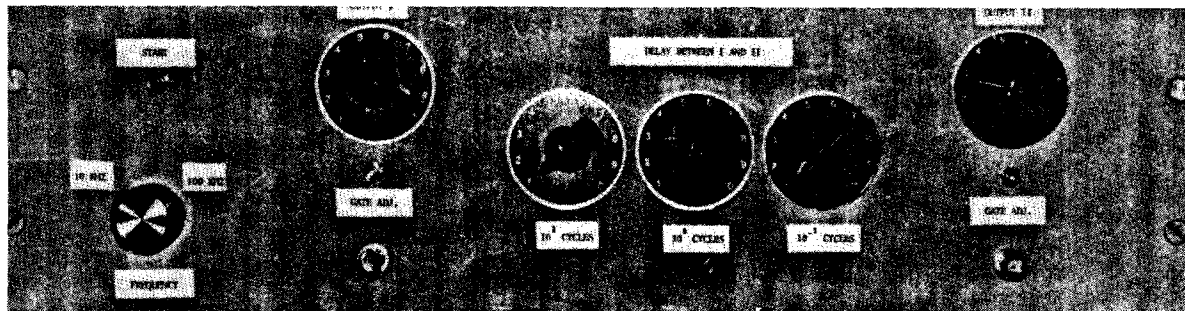


Figure 2.18. Panel (the Frequency will be Adjustable up to 500 kHz Later on).

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. Shumskii¹ - 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

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

²J. 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. Stevens¹ - 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

¹B. 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.

²Allen 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

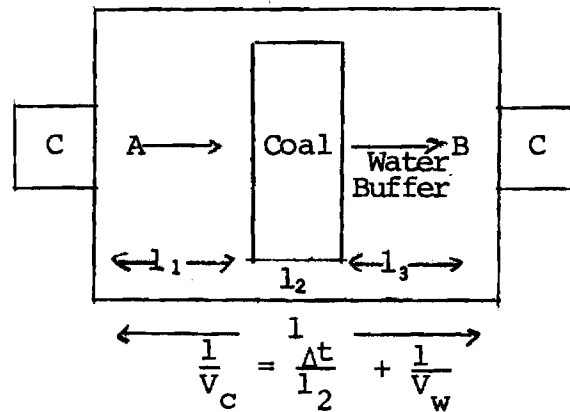
For the determination of the attenuation coefficient, we consider the configuration shown in Figure 3.2. Ensuring continuity of pressure and velocity at each coal-water interface leads to the following relationship between the transmission coefficient, T , and the acoustical properties of coal and water:

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

Here K and δ are defined by:

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

with Z_w the characteristic impedance for water and Z_c



- 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.

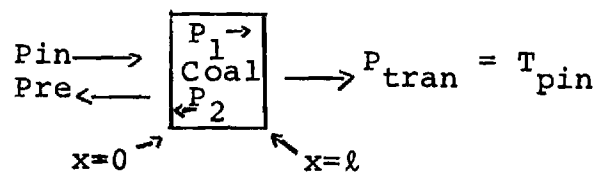


Figure 3.2. Determination of Reflection and Transmission Coefficients.

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 $\exp(-2\alpha l)$. Thus we can obtain an initial

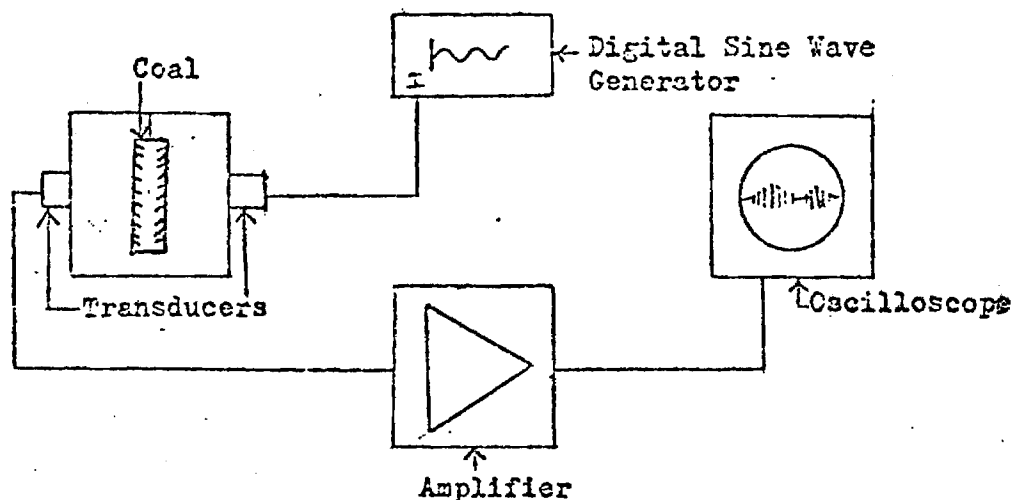


Figure 3.3. Layout of Experimental Apparatus.

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.

¹J. 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.

²B. 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.

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

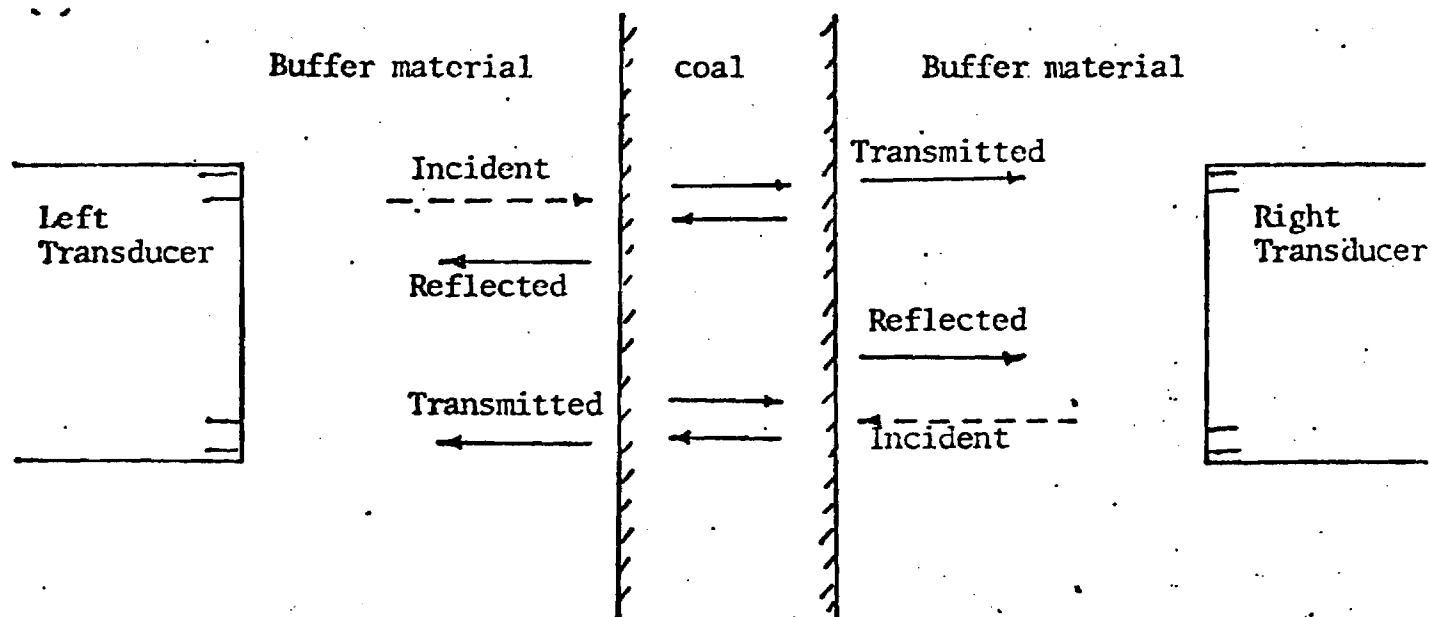


Figure 4.1. Experimental configuration for echo-cancellation method. The incident waves from left and right are expressed as $P_{in,L} = A \exp i(kx - \omega t)$ and $P_{in,R} = B \exp i(ky - \omega t)$, respectively. The pressure received at the left transducer is $P_{ref,L} + P_{tr,R} = R P_{in,L}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

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

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

and

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

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

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

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

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

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

and

$$4\theta^2(1+y)G^2 = X^2[\sin^2\theta + \sinh^2(x\theta)][X^{-4}\theta^4(1+y) - 2X^{-2}\theta^2(1-y) + 1] \quad (5)$$

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 $\alpha l (=x\theta)$ 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

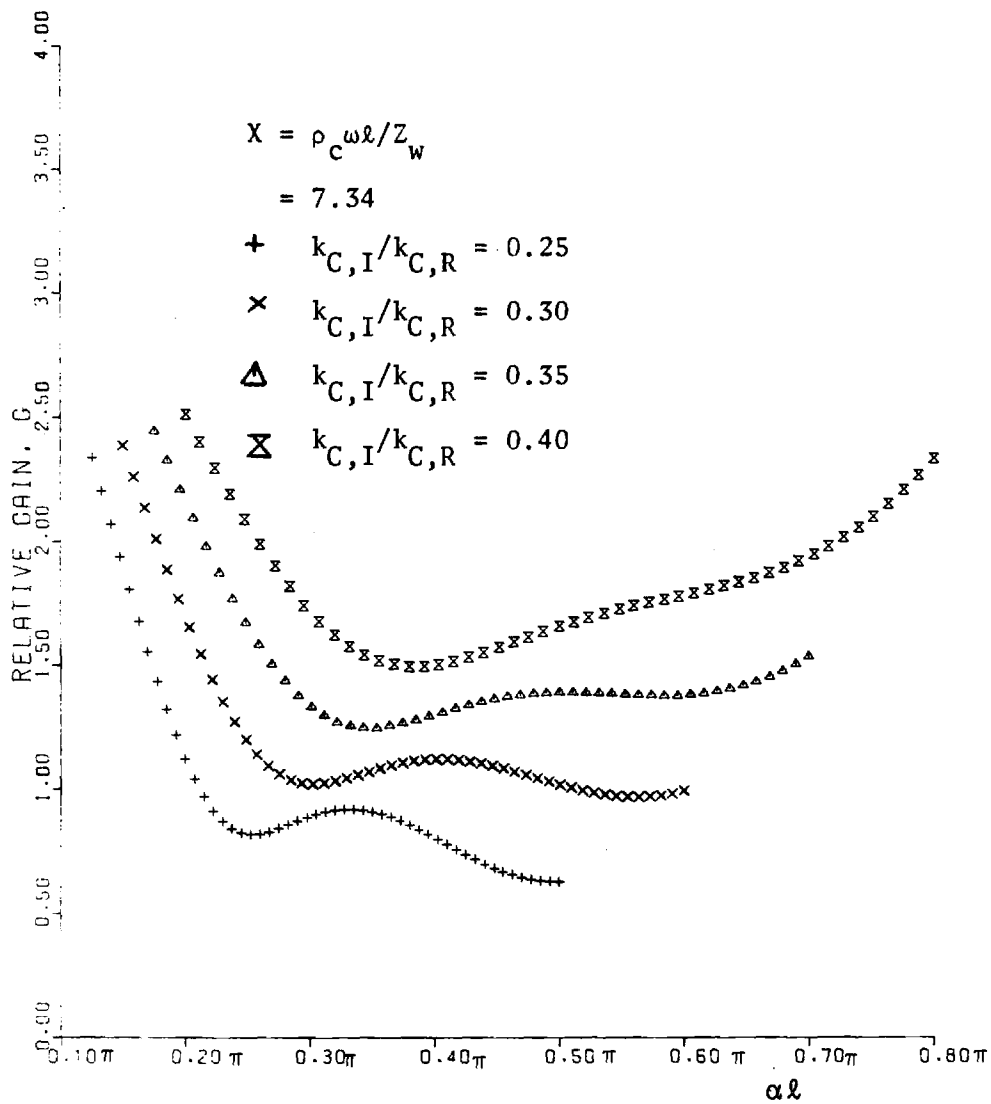


Figure 4.2. Plot of the Relative Gain, G, versus αl for Fixed $X = 7.34$, and Various Other Ratios of $k_{C,I}/k_{C,R} = x$.

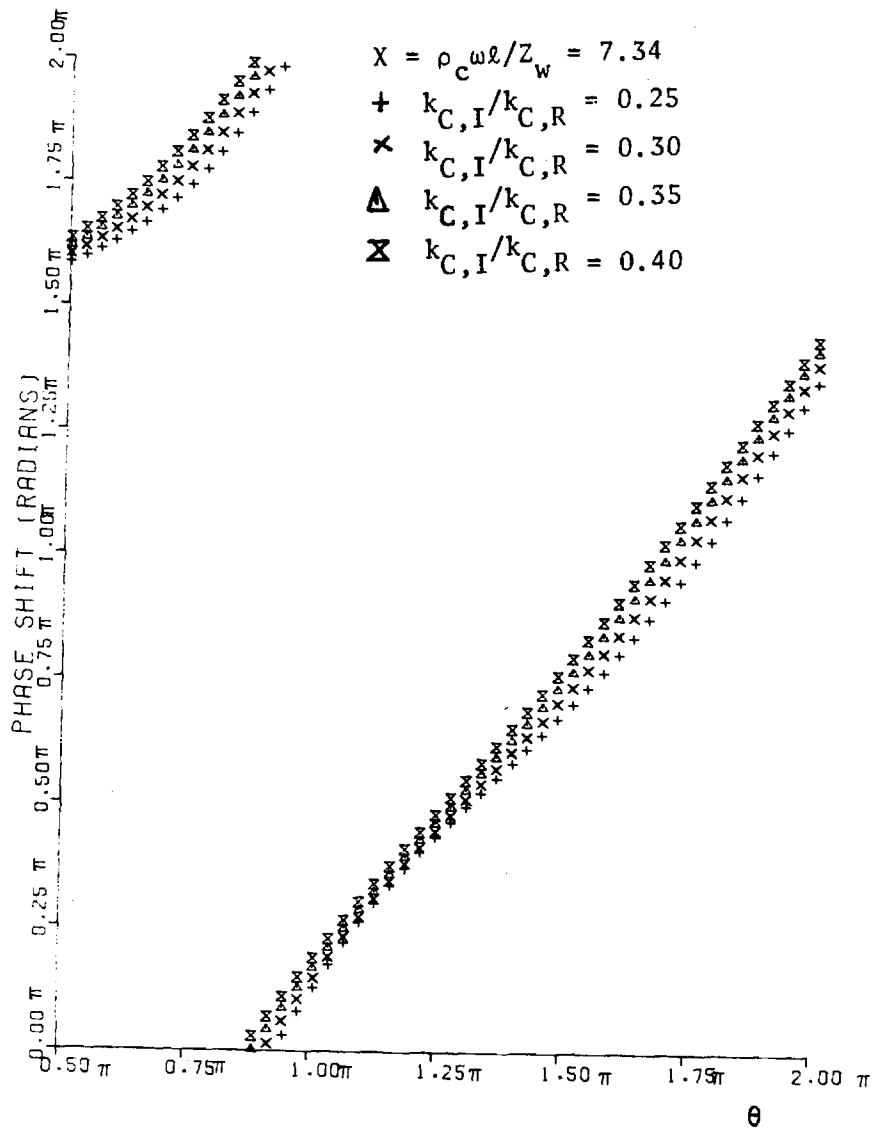


Figure 4.3. Plot of the Phase Angle, θ (radians) versus $\alpha \ell$ for Fixed $X = 7.34$, and Various Ratios of $k_{C,I} / k_{C,R} = x$.

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 iteration 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.

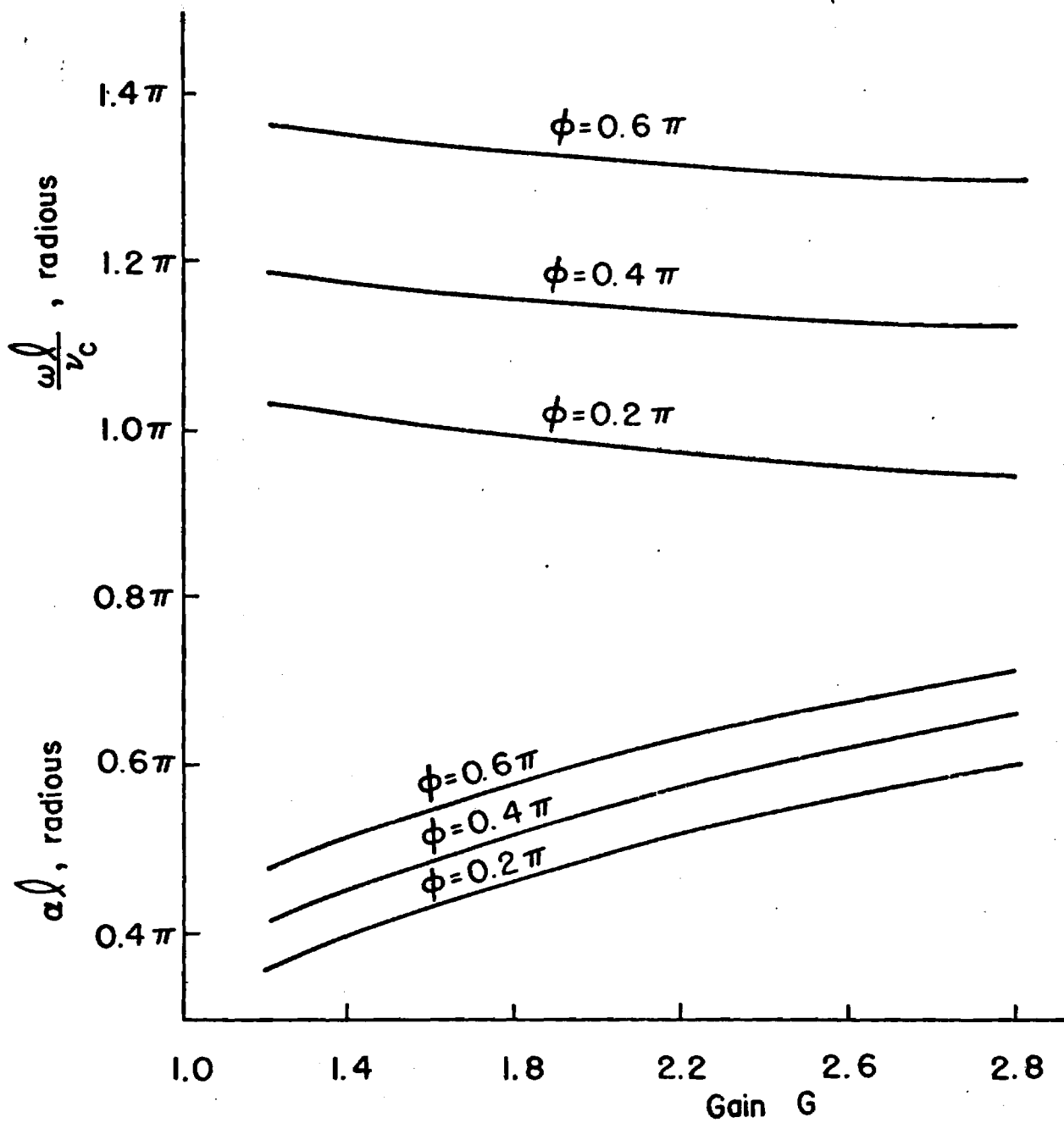


Figure 4.4. Determination of ν_c and α from G and ϕ .

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 = $2.5 \times 10^{-4} \text{ m}^{-1}$) 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.

Knopoff² found that for earth materials, the internal friction Q^{-1} is almost independent of frequency in the low

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

²L. 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. Mason¹ 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 Luche² by considering the motion of the dislocations. The momentum equation is:

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

and the equation of motion of the dislocation is:

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

¹W. 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.

²A. 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,

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

A = total length of movable dislocations

a = dislocation strength,

ℓ = loop length of dislocation,

μ, λ = Lamé's constants,

subject to:

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

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

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

and

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

where

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

$$\omega_0 = \pi(C/A)^{1/2} \ell$$

$$D = \omega_0 A/B,$$

v = velocity of propagation,

$$\Omega = \omega/\omega_0$$

The frequency-independent part of Q^{-1} is given by Mason¹ as $\beta \Delta(\lambda + 2\mu)/(\lambda + 2\mu)$, where β is a constant. Hence the combined internal friction is:

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

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

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

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

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

¹W. 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.

²J. 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:

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

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

According to the Biot⁴ model, the attenuation constant α may be expressed as:

¹M. 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.

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

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

⁴Biot, 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:

$$\begin{aligned} P_{11} &= 0.80 \\ P_{22} &= 0.15 \\ P_{12} &= 0.025 \\ r_{11} &= 0.97 \\ r_{22} &= 0.06 \\ r_{12} &= 0.015 \\ V_c &= 2.3 \times 10^3 \text{ m/sec} \\ f_c &= 2.6 \times 10^{12} \text{ Hz} \\ L_c &= 1.4 \times 10^{11} \text{ m} \\ \text{then } z_1 &= 6.94 \\ z_2 &= 0.058 \end{aligned}$$

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

²H. 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

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

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 formation¹ 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 two general conclusions from their

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

²N. 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.

Whitehurst¹ 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 Kovac² estimated the molecular weight for bituminous coals to be in the range of 1500-1800. Assuming that bituminous coals are composed of aromatic and hydro-aromatic units linked together, the Heredy-Neuworth

¹D. 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.

²J. 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.

T.I. Minicomputer
Data Module

Nicolet Digital
Oscilloscope

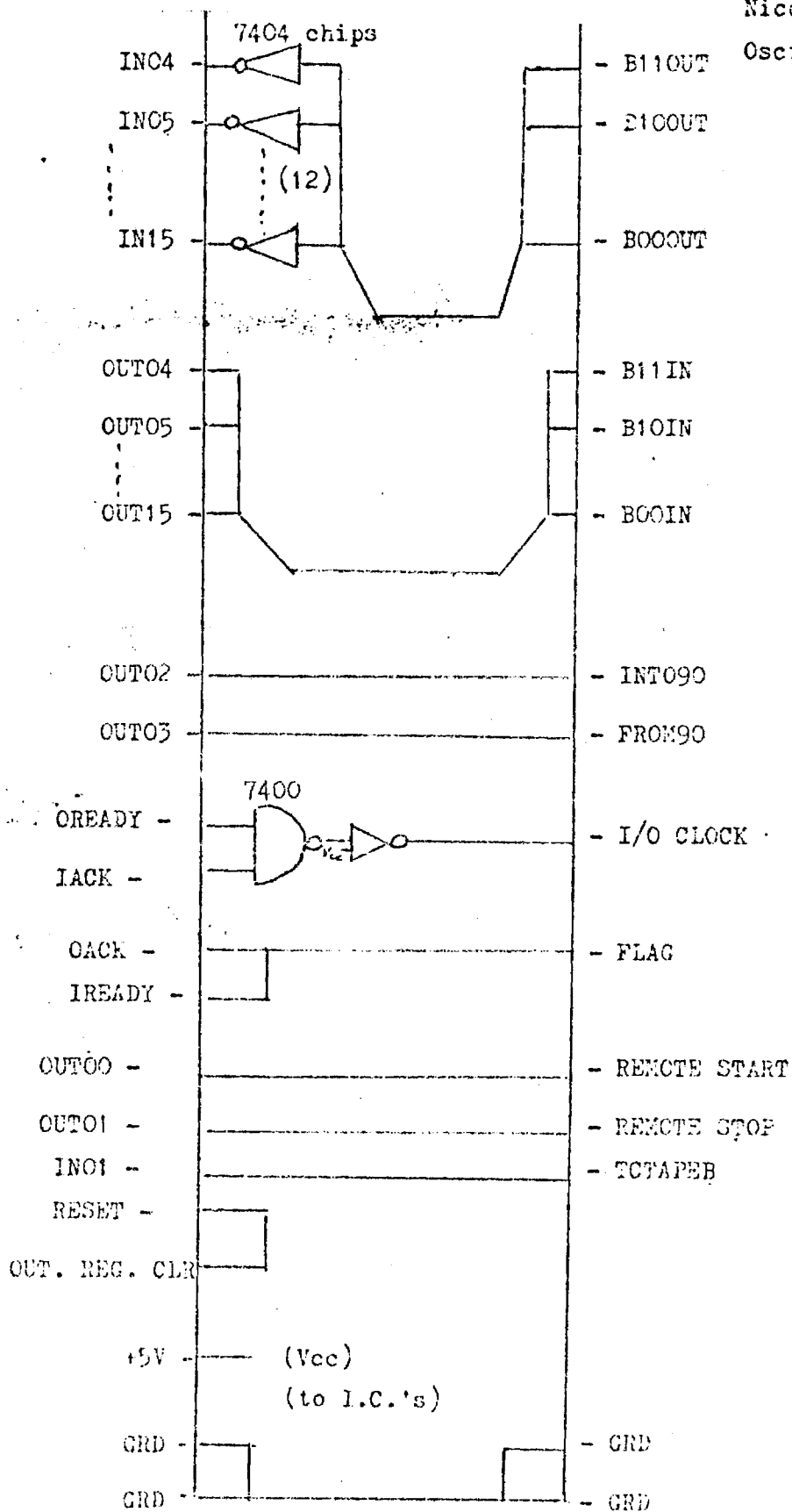


Figure 6.1. Connection of I/O Module to Oscilloscope.

6.4. Input/Output Data Module¹

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

¹Model 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

¹Model 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 Operation¹

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.

¹Model 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 Data¹

Single word transfers between the computer and oscilloscope through the I/O 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										↓		
												logic 0 RDS	
												logic 1 WDS	

Word 2

Bit	0	7	8	9	10	11	12	13-15
Code	unused		B	0	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

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

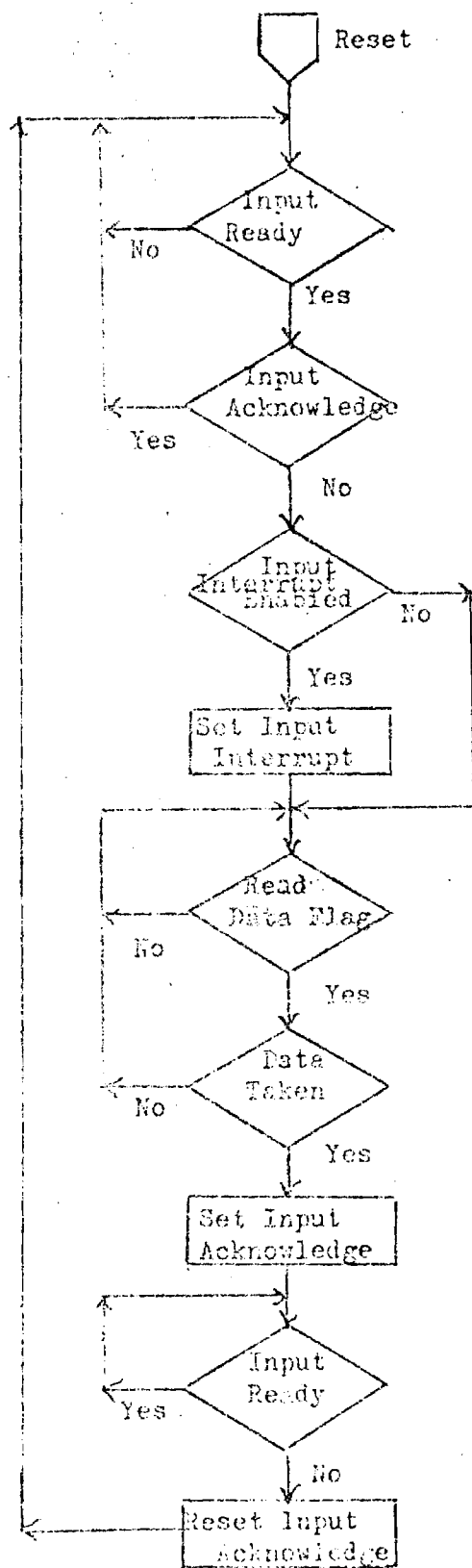


Figure 6.2. Flow Chart for Reading Input.

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:

<u>Bit</u>	<u>Symbol</u>	<u>Function</u>
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 successful 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 Operation¹

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

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

<u>Instruction</u>	<u>Bit 10</u>	<u>Bits 9,11,12,13</u>	<u>Bit 14</u>	<u>Bit 15</u>	<u>Function</u>
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:

<u>Bit</u>	<u>Function</u>
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.

<u>Bit</u>	<u>Function</u>
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 Operation¹

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

¹Model 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, #961961-9734, 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.

<u>LABEL</u>	<u>OPERATOR</u>	<u>OPERAND</u>	<u>COMMENT</u>
1	<u>8</u>	<u>13</u>	<u>30</u> - 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

<u>LABEL</u>	<u>OPERATOR</u>	<u>OPERAND</u>	<u>COMMENT</u>
	DATA	0	send contents of register
TRAP	DATA	0,0	loop for checking interrupts
<u>1</u>	<u>8</u>	<u>13</u>	<u>30</u> - 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:

<u>Instruction</u>	<u>Bit 10</u>	<u>Bits 9,11,12,13</u>	<u>Bit 14</u>	<u>Bit 15</u>	<u>Function</u>
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:

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

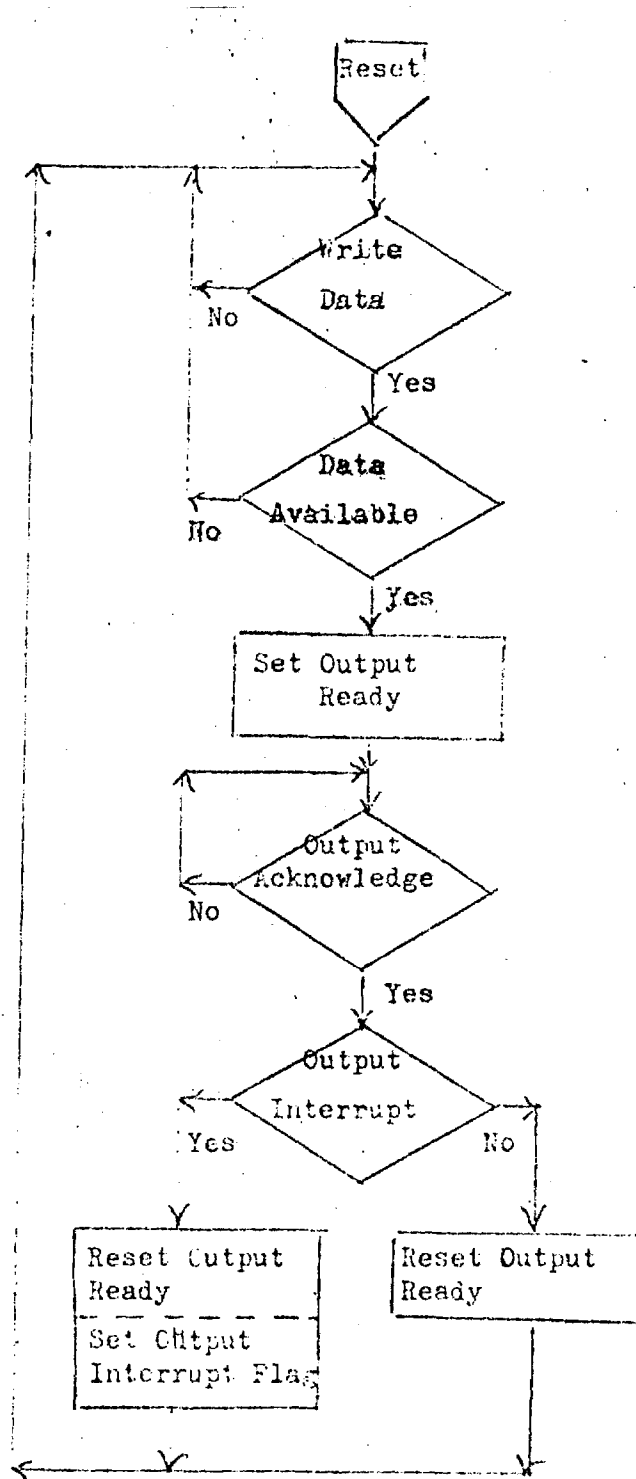


Figure 6.3. Flow Chart for Writing Output.

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.

output word - transfer a 16 bit word from the CPU to the Data Module

output bit - 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. Programmed Write Operation. 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.

<u>LABEL</u>	<u>OPERATOR</u>	<u>OPERAND</u>	<u>COMMENT</u>
<u>1</u>	<u>8</u>	<u>13</u>	<u>30</u> - 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
<u>1</u>	<u>8</u>	<u>13</u>	<u>30</u> - 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 Program¹

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

¹Model 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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