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Report

FEASIBILITY OF REMOTE CONTROL AND DEVELOPMENT OF REMOTE CONTROL DEVICES AND SENSORS

Continuous Mining Machine Seam Interface Sensors

*Ronald F. Steinberg
John T. Ioannou
Sarkis Barkhoudarian*

*Bendix Research Laboratories
Bendix Center
Southfield, Michigan 48076*

National Mine Health & Safety Academy
Beckley, WV 25802

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| 16. Abstract <p>This report presents the results of the study and experimentation on coal-seam interface sensing using the acoustic pulse-echo technique. This method was chosen for further development subsequent to initial feasibility studies investigating other acoustic, electrical, magnetic, nucleonic, and mechanical techniques. The design and construction of acoustic transducers and coupling techniques are discussed and the electronic equipment used in conjunction with the transducers is described. Laboratory coal simulation experiments are described and the results of acoustic transmission and reflection laboratory experiments, using coal samples from various sources, are presented. It was found that the propagation of acoustic energy varied widely in different coal samples. Because of difficulties encountered in laboratory experiments, an underground field test was performed for the purpose of evaluating the effectiveness of the technique for measuring coal thickness in situ prior to final hardware design and construction. The results of the field test, which showed that detection of the coal seam interface was difficult using state-of-the-art techniques because of competing signal returns, are discussed. Recommendations are made that further development of the acoustic pulse-reflection technique be shelved and that detailed information be obtained from the British Coal Board regarding the nucleonic (gamma-ray) backscattering probe for measuring coal thickness.</p> | | | | | |
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FOREWORD

The purpose of this final report is to present the results of the study and experimentation on coal seam-interface sensing using the acoustic pulse-echo technique.

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SECTION 1
INTRODUCTION

The concept of remotely or automatically controlling continuous mining machines (CMM) for coal mining purposes pointed out the need for sensors that could provide guidance information. One such need is for a sensor capable of measuring the thickness of coal remaining on the roof and floor of a coal seam so that the CMM can be controlled to mine just the coal seam and not the roof and floor material. In addition, it is often desirable to leave a given thickness of coal on the roof for roof control purposes.

During the first part of this contract period (a feasibility study), several conceptual methods of measuring the coal-roof interface thickness were evaluated. They included:

- Acoustic reflection (Pulse-Echo Technique)
- Acoustic refraction
- Acoustic resonance
- Acoustic scattering
- Electrical resistivity
- Electrical dielectric constant
- Magnetic susceptibility
- Gamma-ray backscattering
- Mechanical drilling methods

An evaluation and comparison of these techniques was presented in the Preliminary Design Review document, "Feasibility of Remote Control and Development of Remote Control Devices and Sensors, Vol. 2, Continuous Mining Machine Seam Interface Sensors," Bendix Report No. 6040, November 1971. The tabular comparison of these methods is repeated here in Table 1-1.

Table 1-1 - Comparison of Coal Seam Interface Sensor Candidate Techniques

| Measurement Technique Considerations | Acoustic Reflection | Acoustic Refraction | Acoustic Resonance | Acoustic Scattering | Electrical Resistivity | Electrical ⁴ Dielectric Constant | Magnetic ⁵ Susceptibility | Mechanical Drilling | Gamma-Ray Backscattering |
|---|--|---|--|------------------------|--|---|--------------------------------------|---|--|
| Range of thickness measurement in coal | 1/2" - 12" ¹ | Most useful for layers thicker than 12" | 1/2 - 12" | Approx. 1" | 0.75" - 12" | Approx. same as resistivity method | NA | 0 - 12" ⁶ | 0 - 7" ⁸ |
| Resolution capability | One wavelength in coal (<1/2" for f = 100 kHz) | > 1/2", poorer for thin layers. | + 1/2" if contacting transducers used. | NA | +1/2" | NA | NA | <1/2" ⁷ | 1"* |
| Effect of substrate layer (shale, etc.) on resolution | No effect on time delay of reflected signal ² | Small changes in substrate properties cause large errors in apparent thickness measurements | Negligible for given substrate material, affected by change in substrate mat'ls. | Determines calibration | 5% change in substrate ρ results in 19 - 165% error in resolution | NA | NA | Small, depends on type of sensor used. Will affect tool wear. | Scme ⁹ |
| Effect of measurement on coal layer (damage) | None | None | None | None | None | NA | NA | Leaves hole in coal layer. | None |
| Sensor reliability | Good ³ | Poor | Good ³ | NA | Good | NA | NA | Compatible with current mine equipment. | Good* |
| Serviceability of sensor system | Good | Good | Good | NA | Good | NA | NA | Good | Good* |
| Frequency of calibration required (on-site or lab) | Only periodic to compensate for changes in acoustic velocity of coal (on-site) | Often to compensate for changes in coal and substrate acoustic velocities (on-site). | Only periodic to compensate for changes in acoustic velocity of coal (on-site) | NA | Often, to compensate for slight changes in coal or substrate resistivity (on-site) | NA | NA | Periodic | Not known, but probably depends on changes in coal and substrate properties. |
| Measurement time required | < 1 msec, continuous measurements possible | < 0.1 second | 2 seconds* | < 0.1 second | <0.1 second | NA | NA | Approx. 30 seconds | Approx. 10 seconds |
| Safety hazards | None | None | None | None | None | NA | NA | None | Radioactive source used ¹⁰ |
| Good for roof and/or floor | Both | Probably roof only | Both | NA | Both, if floor is dry | NA | NA | Both | Both |

* Indicates estimate

¹ Best accomplished in two separate ranges, for example, 1/2" - 3", 2-1/2" - 12".

² Amplitude of reflected signal varies with acoustic reflection coefficient at interface. As reflection coefficient approaches zero, amplitude of reflected signal decreases.

³ Assuming good coupling of sensor to coal surface.

⁴ Technique not analyzed in detail because at frequencies for which displacement current becomes effective, the dielectric constant contrast due to the polarization effect of the porewater is lost.

⁵ Technique not analyzed in detail because presence of ferromagnetic material in mine (CMM itself) would mask any change due to coal thickness.

⁶ Could be extended to about 4 feet with longer measurement times.

⁷ Resolution of drilling tool, resolution of system depends on type of sensor used.

⁸ May be extended with stronger sources.

⁹ Magnitude of effect not known, but calibration depends on backscattering properties of both coal and substrate.

¹⁰ With properly designed sensor, safety hazards may be more psychological than real.

The Old Ben Coal Corporation Mine #24, located in Benton, Illinois, was selected as the underground field test site. This site was chosen over the USBM Experimental Mine in Bruceton, Pennsylvania, primarily because it is an operating mine and the test locations would be prepared by a continuous mining machine. During the experimental field test, maximum use was made of existing laboratory equipment.

In the analysis of the experimental field test data, good correlation between detected signals and the structure of coal samples obtained at the individual test locations was obtained. Detected signals were correlated with the coal-roof interface, but these signals are not easily separated from reflections from other foreign layers in the coal. The question of whether cracks are formed in the roof coal during the mining operation was not answered with certainty. Cracks definitely occurred in the coal samples obtained from the roof, but these could have been incurred as a result of extracting the coal samples. Whenever a crack did occur, it occurred at a plane in the coal corresponding to a foreign layer. As a result of the field test, it was determined that the acoustic technique is not a general solution to the problem of measuring coal seam thickness. It appears that it might still be applicable in mines where few or no foreign layers exist in the head coal. Before more time and money is invested in the acoustic method, however, a survey of the structure of head coal in many mines should be made to determine what percentage of mines have head coal without these foreign layers.

Section 2 of this report describes the experimental laboratory work carried out during this contract. Section 3 reports on the underground field test and the analysis of the experimental data. Section 4 summarizes the information obtained pertaining to the gamma-ray back-scattering sensor. Section 5 gives the conclusions pertaining to the acoustic coal seam interface sensor and the recommendations for future work are given in Section 6.

SECTION 2

LABORATORY STUDIES AND EXPERIMENTS

In this section, the design and construction of acoustic transducers and acoustic coupling techniques are discussed. The electronic equipment used in conjunction with the transducers is described. Laboratory coal simulation experiments are described and finally, the results of laboratory experiments to measure the acoustic transmission and reflection in various coal samples are described.

2.1 DESIGN AND CONSTRUCTION OF ACOUSTIC TRANSDUCERS

The choice of acoustic frequency in the pulse-echo method is based on the resolution, surface roughness, and range of the measurement. The contract specifies a range of 0 to 12 inches with a resolution of $\pm 1/2$ inch. To obtain a wavelength of $1/2$ inch in a typical coal having an acoustic velocity of 10^5 inches/sec requires a frequency of 200 kHz. However, when long travel times are measured, it is sometimes possible to detect a fraction ($1/2$ or $1/4$) of a wavelength, so that the frequency can be lowered to 100 kHz.

For the case of short travel times, i.e., thin coal layers, the transducer ringing prevents measurement for a short period of time which results in an effective dead measurement zone. Assuming that the number of ringing cycles is constant, the use of higher frequency signals results in a shorter ringing period and therefore a shorter dead zone. In other words, with higher frequencies (such as 500 kHz), interfaces closer to the surface can be detected. However, the use of higher frequencies results in larger signal attenuations. Based on the above trade-offs, a reasonable range of operating frequency is 100 kHz to 500 kHz.

For this frequency range, the most suitable transducers are those incorporating piezoelectric materials as their sensitive elements.

Lead zirconate-titanate and lead meta-niobate ceramic discs of various frequency thickness-mode resonances were selected for their high transduction and low Q, respectively.

Q is a dimensionless factor indicating the amount of ringing of a system and is related to the acoustic absorption coefficient by

$$Q = \pi/\alpha\lambda$$

where α = acoustic absorption coefficient in inverse meters

λ = wavelength in meters

Assuming only acoustic absorption losses, the signal attenuation is a function of Q and the number of wavelengths n:

$$A = A_0 e^{-\alpha x} = A_0 e^{-\pi x/Q} = A_0 e^{-n\pi/Q}$$

Thus at $n = Q/\pi$, the amplitude becomes e^{-1} or 0.37. At $n = Q$ wavelengths, the amplitude decreases to ~ 0.04 . At 200 kHz with $Q = 4$, the reflected signal will be attenuated to 4 percent of the initial ringing value after 20 μ sec (4 cycles). This means that coal thicknesses less than 2 inches, the dead zone, cannot be detected. The effect of transducer Q on the coal thickness that can be detected is shown in Figure 2-1.

Another consideration in the design of transducers relates to the method of coupling the acoustic energy into and out of the coal medium. Since the coal surface is not smooth and planar, simple pressure contacting of the transducer to the coal is not possible. An intermediate coupling medium must be used. Two basic coupling techniques were investigated during the feasibility stage of this contract: one using essentially a contained fluid couplant between the transducer and coal and the second, a water jet between the transducer and coal. The advantage of the second method for this purpose is that it is noncontacting coupling, whereas the first requires a pressure contact to the coal.

surface. The water jet method is therefore more suitable when other than static measurements are required (for example, when the CMM is operating and/or moving).

The design of a water-jet coupling fixture was described in the Preliminary Design Document, Volume 2. The design of this fixture incorporated transducer backings that were conical in form so that the flow of water around the piezoelectric disc did not generate cavitation in front of the disc. (See Figure 2-2).

Since transducers meeting the study's requirements of low center frequency, low Q, and compatibility with water-jet nozzle configuration were not commercially available, they were designed and fabricated in-house. Commercial lead zirconate-titanate (PZT-4 or PZT-5) discs are readily available in maximum thicknesses of 1/2 inch and diameters of 2.5 inches. However, these discs have a Q in air of approximately 400, a value too high for the present application. Therefore the Q was reduced by an acoustically absorptive backing material having an acoustic impedance close to that of the piezoelectric ceramic. When this backing material is applied to the ceramic disc, very little energy is reflected from the back of the disc, and energy transmitted into the backing material is almost entirely absorbed.

Backing materials that were tested included lead, zinc, sintered brass, and tungsten-powder-impregnated epoxy. When applied to the piezoelectric discs with silver epoxy, the first three materials proved unsatisfactory. Upon investigation, it was found that the silver epoxy was not adhering to the disc uniformly and could be causing voids. The last material, 80 to 325 mesh tungsten powder impregnated in 1266 Stycast epoxy (manufactured by Emerson and Cuming), gave the best result. The Stycast epoxy was also used to cement the backing material to the piezoelectric disc. This combination of backing material and cementing agent resulted in reduction of Q to ~5.

Pentagonal slots were machined in the piezoelectric discs to minimize the radial-mode resonance, and the assembly was coated with PRC-1538

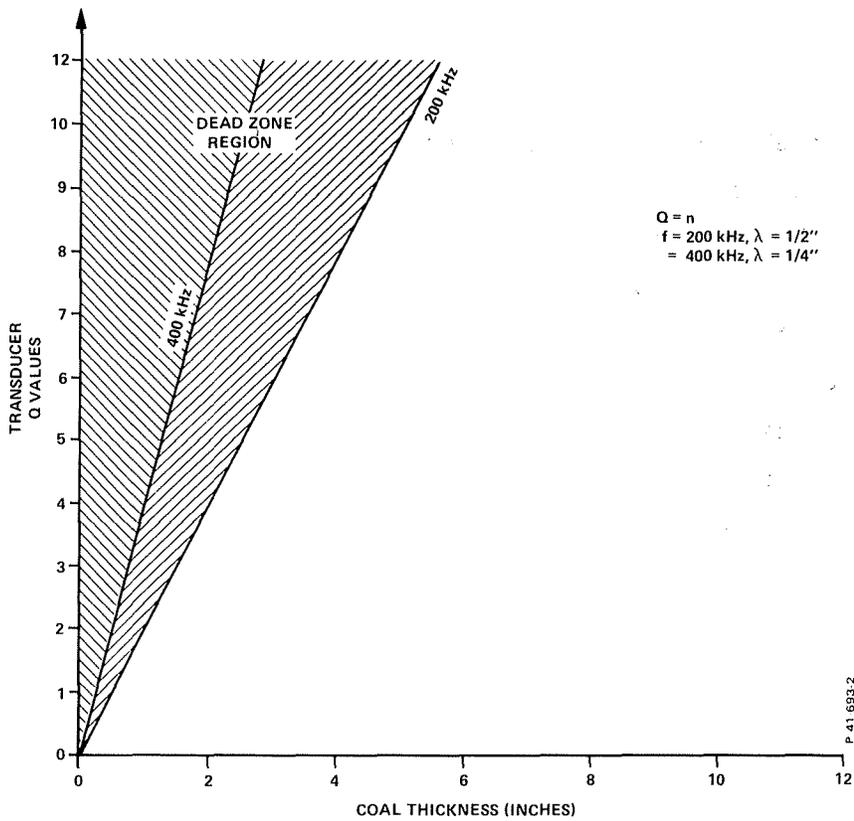


Figure 2-1 - Relationship Between Transducer Q and Coal Thickness

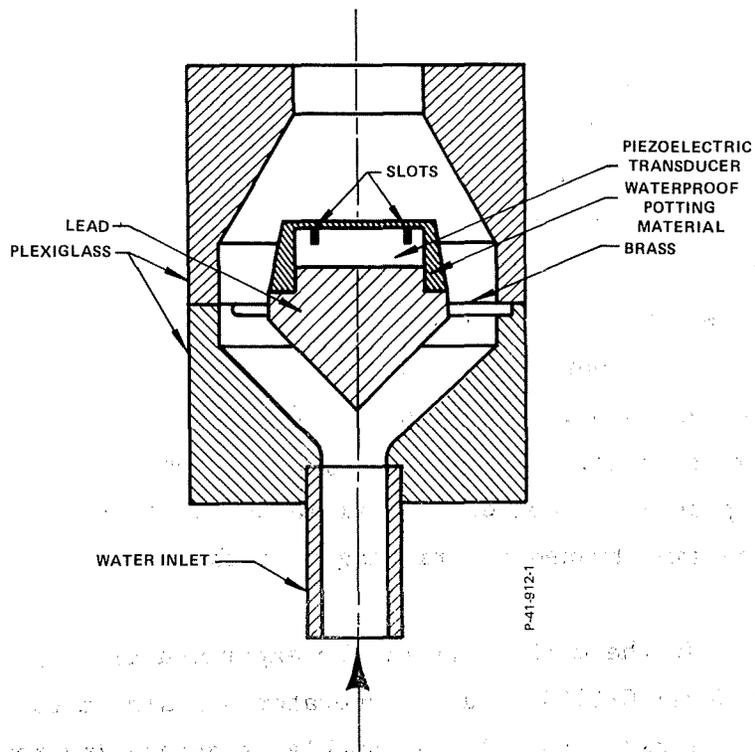


Figure 2-2 - Water Jet Assembly for Transducer-to-Coal Coupling

epoxy for insulation. Two transducer assemblies having low frequencies and low Q are shown in Figure 2-3. Figure 2-3a shows an assembly having pentagonal slots all on one face; in Figure 2-3b, two of the slots are on one face of the transducer and the rest on the other face.

In addition, commercial, low-Q (2), low-capacitance (900 pF), model J-302 transducers, having the frequency response shown in Figure 2-4, were obtained from Automation Industries. However, these transducers were not available in center frequencies lower than 400 kHz and did not have the configuration suitable for water jet assembly.

2.2 TRANSDUCER EXCITATION AND RECEIVING SYSTEM

2.2.1 Separate Transmit and Receive Transducer System

Figure 2-5 shows the schematic of the electronic excitation and receiving system used for much of the laboratory experiments and the experimental underground field test. The transducer drive, or excitation, part of the system consists of a pulse generator, function generator, and power amplifier. The pulse generator, a Hewlett-Packard Model 214, was used to trigger the function generator at a repetition rate of 1 kHz and to provide a sync signal to the oscilloscope. The function generator, Interstate Electronic Company Model F-34, was used to generate the desired waveform. It is capable of generating frequencies from 1 Hz to 3 MHz in continuous, pulse-modulated, and frequency-modulated modes. Its maximum output is 10 volts peak into a 50 ohm output impedance. This signal is amplified by a Krohn-Hite Model DCA-50 power amplifier which was directly coupled to the transmitting transducer. The power amplifier has an output impedance of 300 ohms and a maximum output voltage of 250 volts peak. The relatively low output impedance amplifier was used to provide a good electrical match to the transducer. This prevents excessive transducer ringing when the excitation voltage is removed.

In the early part of the experimental program, a James Electronics Model C-4960 impulse generator was also used to excite the transmitting transducers. It is capable of generating repetitive pulses

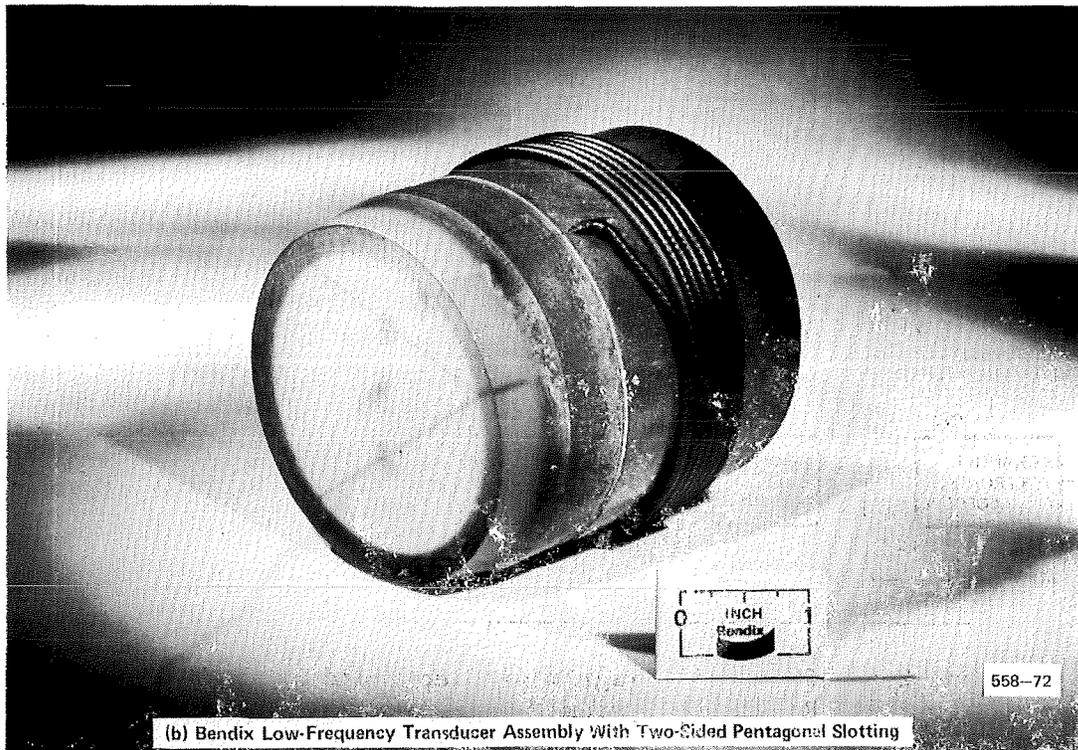
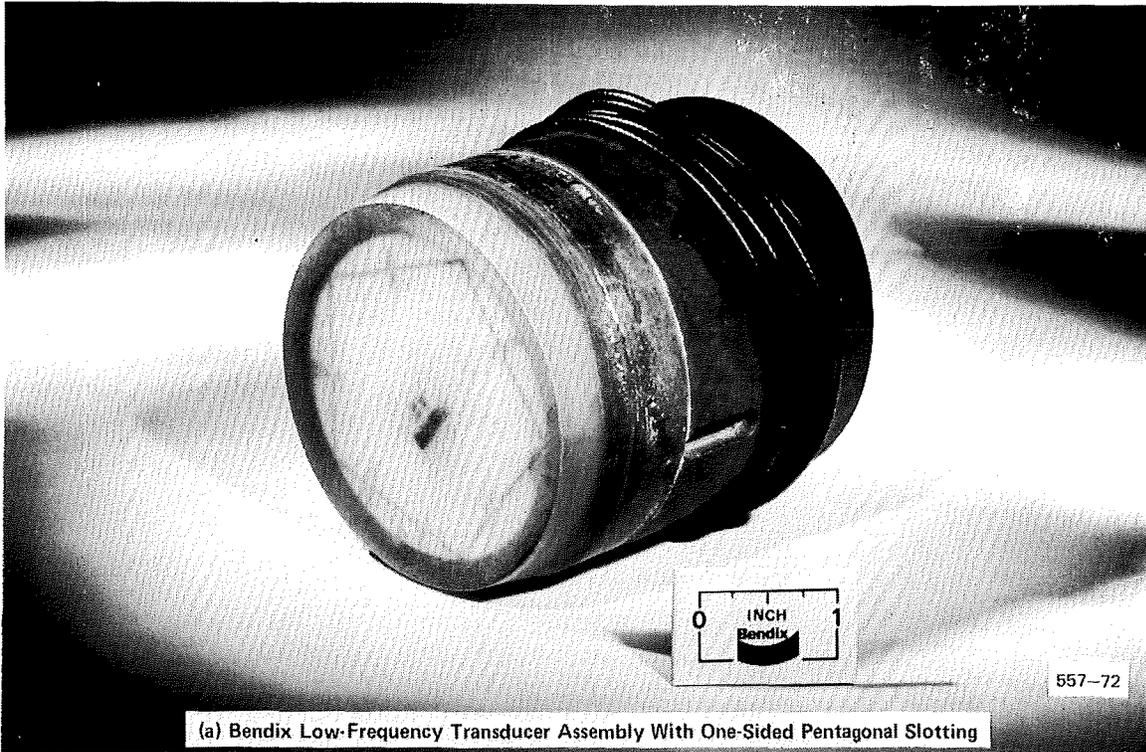


Figure 2-3 - Slotted Low-Frequency Transducer Assemblies

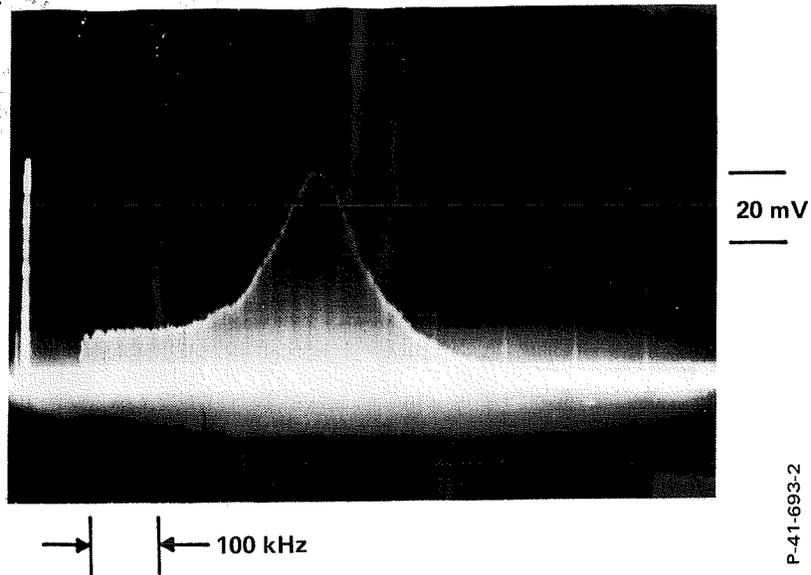


Figure 2-4 - Frequency Response of Automation Industry Transducer Detected by Identical Transducer

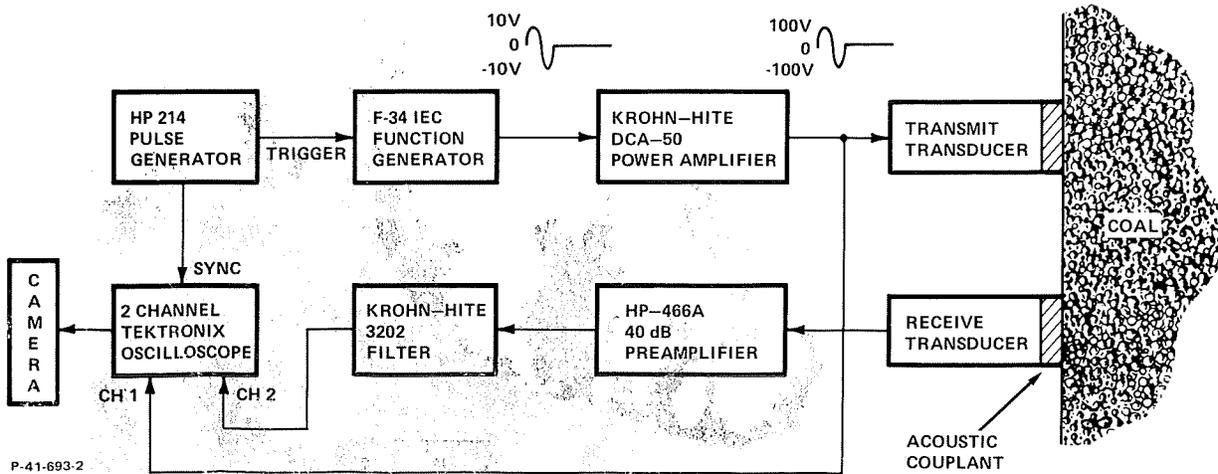


Figure 2-5 - Schematic Diagram of Electronic Excitation and Receiving System

up to 1600 volts peak amplitude with a rise time of approximately 1 μ sec. However, its large output impedance, 100 k Ω , combined with the transducer capacitance, resulted in a long time constant and excessive transducer ringing. This generator, although useful for acoustic transmission measurements through coal, was not useful for reflection measurements.

The receiving part of the system of Figure 2-5 consists of a low level amplifier, a filter, and a oscilloscope display. A Hewlett-Packard Model HP-466A, 40 dB amplifier was used to amplify the receiver transducer signal. A Krohn-Hite Model 3202 filter was used to suppress signals outside the desired bandwidth. The filter can operate as a 24 or 48 dB per octave high or low-pass filter or as a 24 dB per octave band-pass filter. The filtered output signal was displayed on one channel of a Tektronix two-channel oscilloscope. The input to the transmitting transducer was displayed on the second channel.

2.2.2 Transceiver Electronic Subsystem

The acoustic pulse-echo technique can employ either a single transducer (known as a transceiver), which functions sequentially as a transmitter and a receiver, or a combination of a transmitting transducer and a separate receiving transducer. In the case of a single transducer, a voltage is impressed across the transducer which radiates an acoustic wave. The transducer is then switched to a receiving mode to detect reflected signals and convert them to a voltage. The advantages of the transceiver mode are:

- Only one transducer is required, instead of two
- Signal beam spreading is less troublesome
- Surface waves from transmitter to receiver are nonexistent
- Coupling between the transducer and the coal surface is simplified

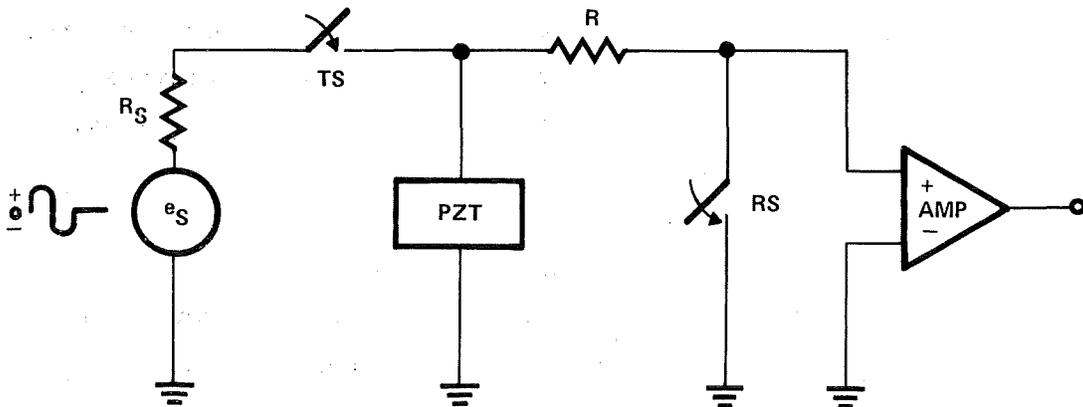
The disadvantages of this mode are:

- It requires much lower transducer Q
- Reflections from transducer backing compete with the reflected signals

To overcome these disadvantages means that transducer oscillations during transmission must be substantially damped out in order to receive low-level return signals, which requires mechanical damping of the piezo-electric element to provide low Q operation. Furthermore, the transducer mechanical backing must be designed such that a negligible amount of the transmitted signal is reflected back to the piezoelectric element.

The separate transducer mode has two problems: the physical separation between the transmitter and the receiver results in some signal attenuation because the reflected signal is off-axis from the receiver; and acoustic surface (radial) waves propagate from the transmitter to the receiver, resulting in false signal returns.

The design concept of a circuit for transceiver operation is shown in Figure 2-6. This circuit imposes the least demanding voltage and switching-time requirements on the electronics of the transceiver. The high-voltage single-cycle sine driver is represented by e_s and source resistance R_s . The letters TS signify the transmit switch, and RS the receive switch, both of which are operated in-phase i.e.,



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Figure 2-6 - Basic Transceiver Design Approach

simultaneously closed or open. The PZT element represents the piezoelectric transducer and R denotes a series resistor which limits the current through RS to a safe value. During the time that e_s is generating a sine-wave voltage, both TS and RS are closed. Thus, the driver sees a parallel load of PZT and R. The value of R is large compared to the reactance of PZT. Meanwhile, the amplifier input is protected by the shorting effect of RS. Also, the current through RS is limited by R. After e_s has returned to zero volts, then TS and RS are both opened: TS isolating e_s from the PZT element, and RS unshorting the amplifier input. Note that neither TS nor RS has to withstand the high voltage associated with e_s , which is $\pm 100V$ peak or higher. The only switching-time requirement is that TS and RS have to open within 5 μsec of activation, in order to be prepared for a reflected signal from a 1/2-inch coal seam depth.

The detailed circuit schematic for the transceiver is shown in Figure 2-7. Switch TS is made up of a bipolar arrangement of 2N3725 transistors and MCT2 phototransistor optoisolators. Switch RS consists of the 2N4393 FET. Resistor R is the 15K resistor in series with the amplifier input. The amplifier is a non-inverting OP AMP with a voltage gain of 2, used as a line driver for capacitive loads. The amplifier output includes a series 51Ω resistor to match the characteristic impedance of RG58U coaxial cable, and the coaxial is terminated with 51Ω at the oscilloscope input. The MCT2 opto-isolator is activated by a trigger pulse ($\approx 5\mu\text{sec}$ wide) obtained from the HP Model 214A pulse generator. The 1 K Ω resistor, shunting the PZT, reduces the PZT capacitive discharge time when settling to zero volts after the single-cycle transmission. The circuitry was assembled into a 7 x 5 x 3 inch aluminum box and was battery powered.

A commercially available transducer which has a sufficiently low Q (<5) to allow proper transceiver-mode operation is the Automation Industries Type J302. However, its construction includes an 0.55-inch semi-rigid backing adjacent to the piezoelectric element, followed by

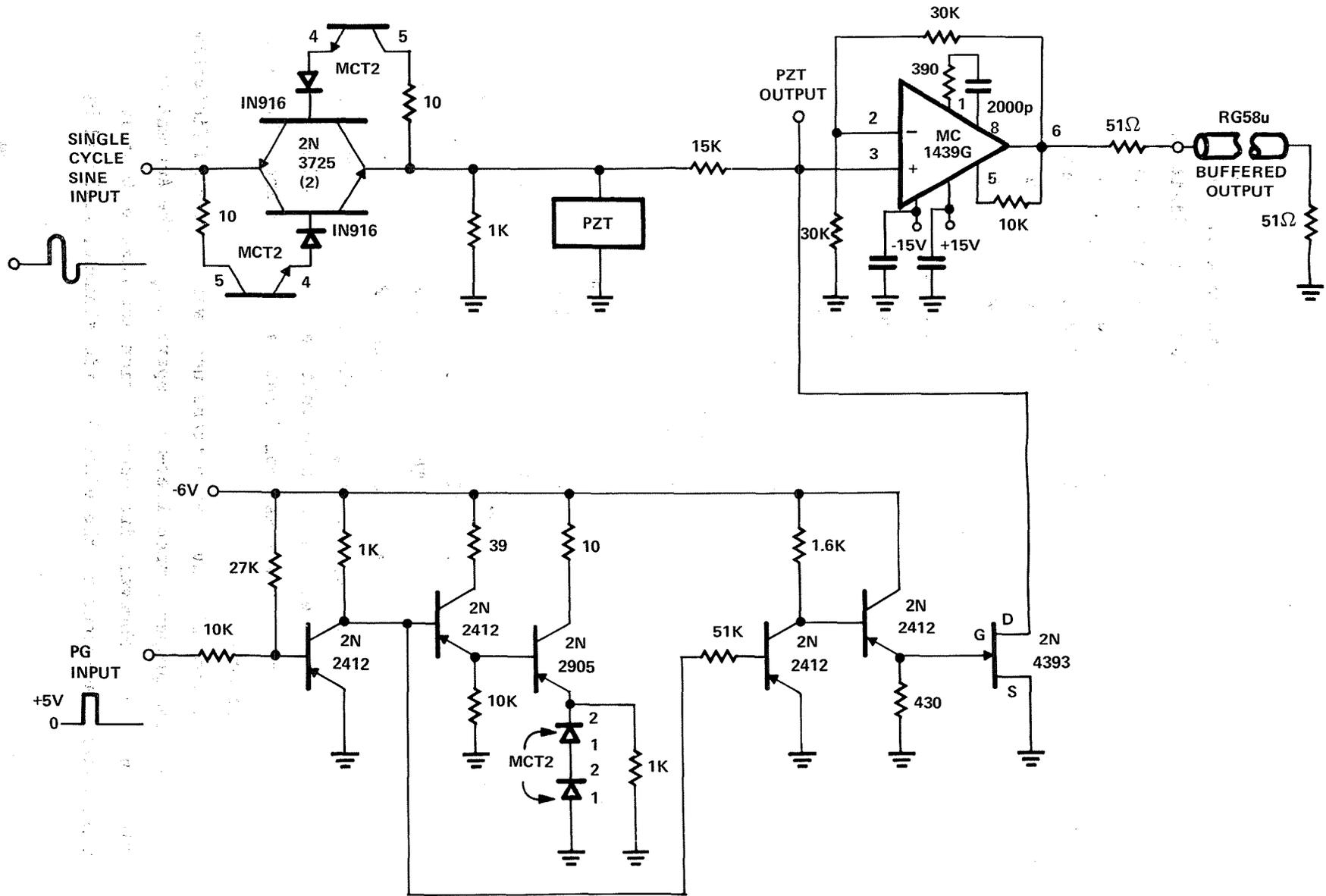


Figure 2-7 - Transceiver Circuit Schematic

an 0.65-inch rigid backing. See Figure 2-8. These interfaces reflected the transmitted signal, which propagated through the backing, back to the piezoelectric element. As a result, false signals appeared at 35 μ sec and at 45 μ sec from the beginning of the transmission. These signals measured 6 mV and 17 mV, respectively, and precluded the measurement of any true reflected signals within a 3-inch coal depth.

For transceiver-mode operation, a low Q (<5) loaded transducer with a backing which reflects negligible ($<100 \mu$ V) signal to the piezoelectric element is required.

2.3 COAL LAYERING SIMULATION EXPERIMENTS

An experiment was conducted to simulate the layering structure of coal in order to investigate the possible effects of layering on reflected

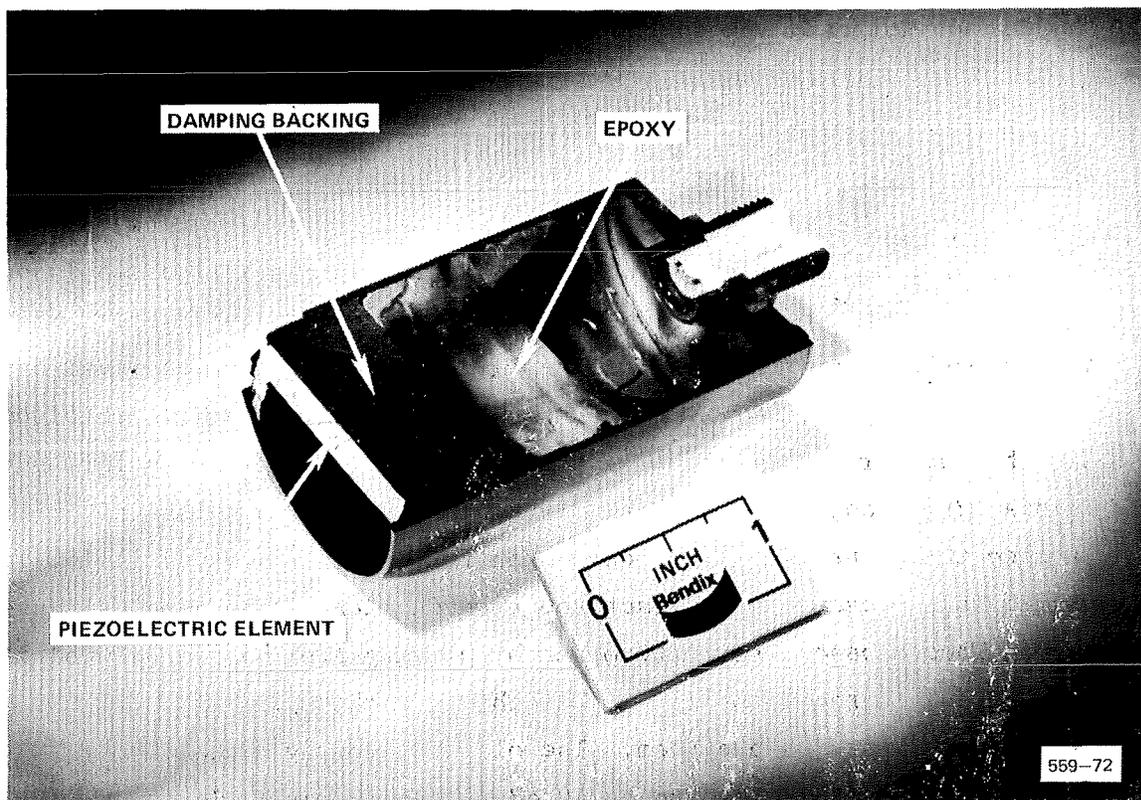


Figure 2-8 - Automation Industries Type J 302 Transducer (Cut-Away View)

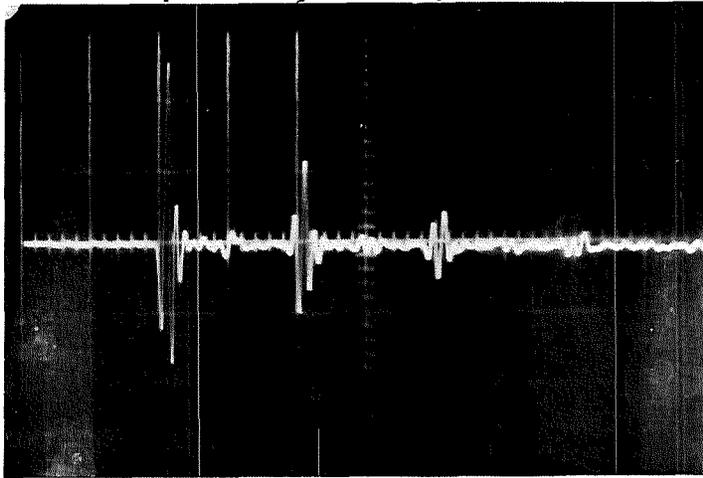
signals. Plexiglas was used to simulate coal because of its similarity in acoustic impedance and velocity. The acoustic velocity of plexiglas is ~ 2.5 km/sec compared to 2.3 km/sec for a typical coal; its density is 1200 kg/m^3 compared to 1300 kg/m^3 for coal, and its acoustic impedance is ~ 3.2 M rayls compared to 3.3 M rayls for coal. The main difference is the existence of layering in coal and the magnitude attenuation of the two materials.

Plexiglas plates were used to simulate the layering effect of coal. A 300 kHz single-cycle sine signal was used to excite the Automotive Industries transducers. Figures 2-9a through 2-9d show, in spite of excessive care to eliminate air gaps between the plexiglas plates, the gradual cluttering of the consecutive bottom reflections and the gradual increase of reflections from intermediate layers as the number of the plexiglas layers are increased from one of 2-inch thickness to eight of 1/4-inch thickness. Therefore, the layering structure can cause erroneous reflections. For example, a 5 percent change in carbonification of bituminous coal effects an 8 percent acoustic reflection. In all the types of coal that have been tested, there are a large number of bands (or layers), e.g., Old Ben Coal has 20 to 30 bands per inch. These layers can be sources of spurious and undesired reflected signals.

2.4 LABORATORY ACOUSTIC EXPERIMENTS WITH COAL

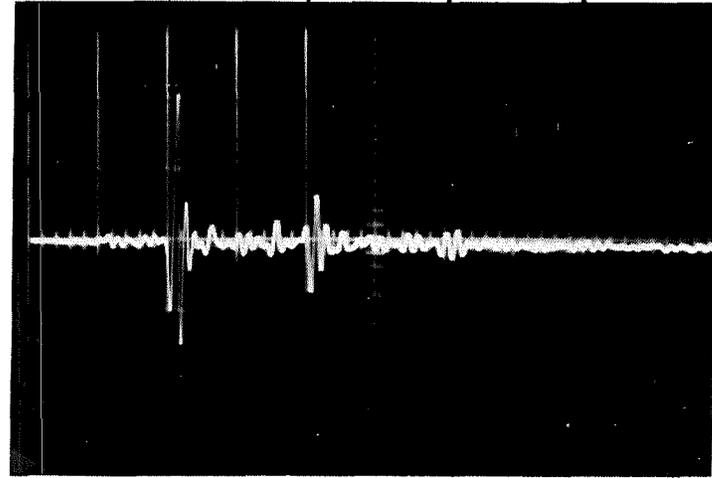
Physical appearance as well as acoustic transmission of various coals obtained from the following U.S. mines were compared: Clinchfield, Virginia; Bruceton, Pennsylvania; Old Ben, Illinois; and Kentucky. To determine the acoustic signal loss, when transmitted through a piece of coal, it is necessary to subtract the transduction losses of the transducers. These losses were determined by placing two Automation Industries transducers in direct contact with each other through a very thin layer of grease or water between them. The electric voltage loss due to transduction was determined to be 40 dB. When a 3-inch-thick plexiglas was placed between the two transducers, the signal loss was 50 dB.

1ST BOTTOM REFLECTION 2ND 3RD 4TH

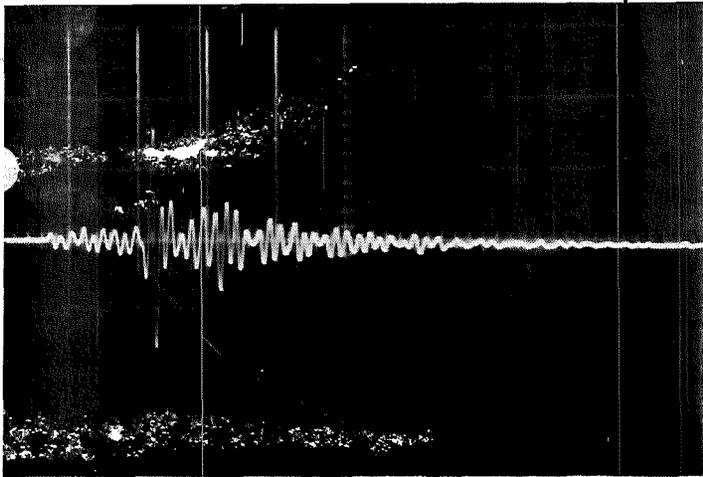


(a) ONE 2" THICK PLATE

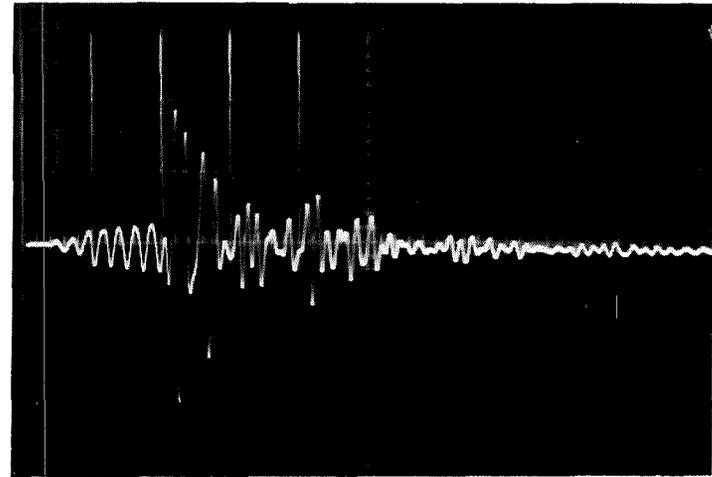
1ST BOTTOM REFLECTION 2ND 3RD 4TH



(b) TWO 1" THICK PLATES



(c) FOUR 1/2" THICK PLATES



(d) EIGHT 1/4" THICK PLATES

20 μ sec

20 mV

Figure 2-9 - Effect of Layering in 2-Inch Thick Plexiglas Slabs

The slight increase in the loss can be due to beam spreading and the acoustic absorption of plexiglas. Since coal and plexiglas have the same acoustic impedance and consequently the same reflection at the transducer-coal interface, any increase in the loss is attributed only to the coal acoustic attenuation. Nearly all laboratory coal samples contained cracks in the bulk of the coal which are probably due to the mining process, handling, and transportation. To overcome this problem, the coal samples were sometimes soaked in water (or other liquids) to fill up the cracks and thus increase the acoustic transmission. The acoustic transmission increased as the time of soaking increased. When a commercial solvent known as Rhinolit (a mixture of isopropanol, ethanol, and methanol) was used for soaking, it enhanced the acoustic transmission drastically even for a very short time of soaking (5 minutes). This can be attributed to the low surface-tension and methane-absorption properties of the commercial solvent.

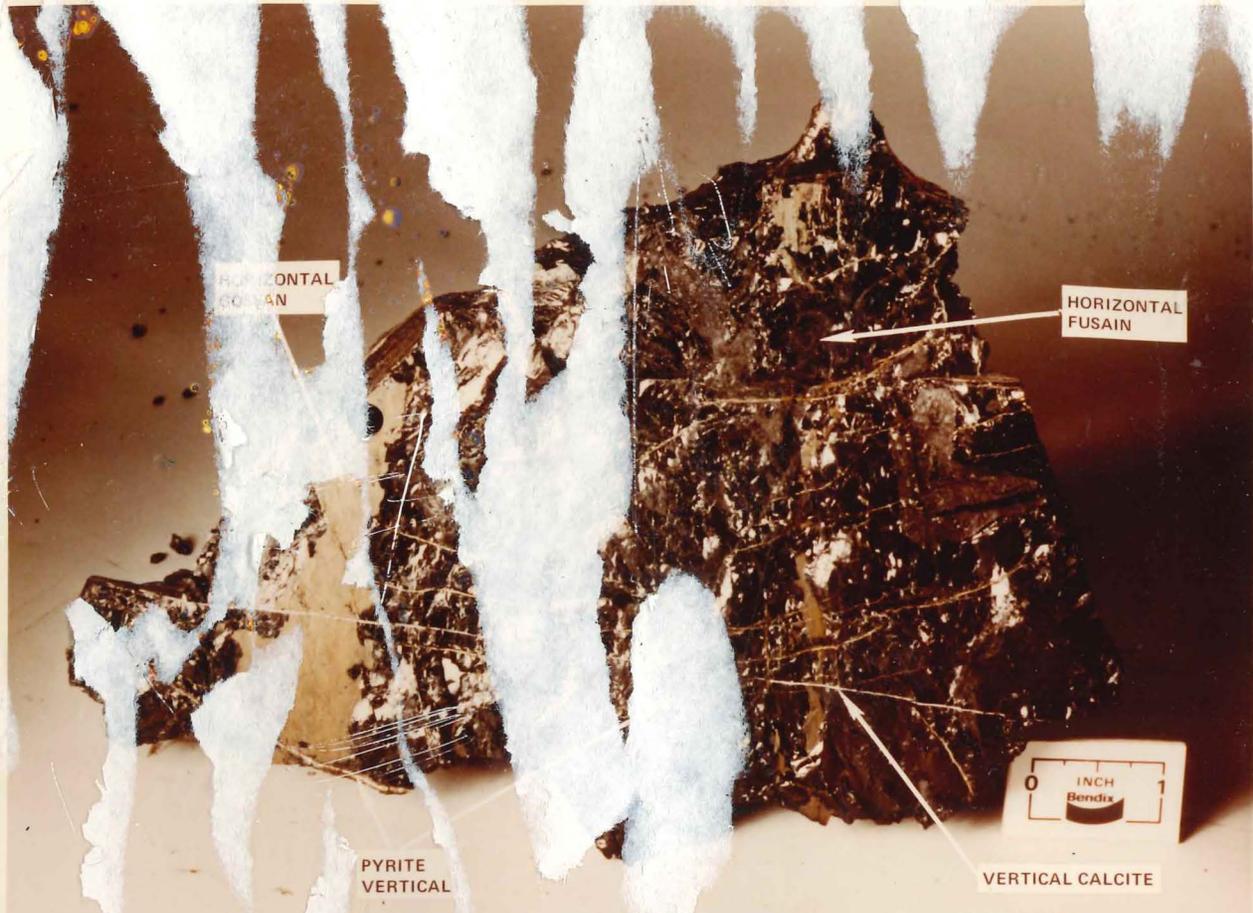
2.4.1 As-Received Old Ben Coal

A 2.3-inch thick, freshly excavated, Old Ben coal piece indicated a total of 120 dB loss at 300 kHz. Subtracting 50 dB for transduction and beam spreading, the remaining 70 dB loss (or 33 dB/inch) is due to the coal absorption, cracks, impurity layers, and the coal layers.

This is much higher than the estimated absorption loss of 6 dB/inch, indicating that the presence of cracks and impurity layers drastically affects the effective attenuation.

Another older slab of this coal, 3.5 inches thick, exhibited even higher losses at 300 kHz, with a 120 dB loss at 50 kHz. The difference in the results from these two samples is probably due to mine cracks or foreign layers in the second sample.

Visual observation of samples from Old Ben indicated a large number of vertically deposited transparent calcite layers as thick as 0.020 inch (Figure 2-10a). In addition, there are many vertical (up to 0.020-inch thick) as well as horizontal layers of shiny yellow



(a) VERTICAL CALCITE AND PYRITE VEINS AND HORIZONTAL FUSAIN PATCH



(b) HORIZONTAL PYRITE

Figure 10 - Layers in C...

pyrite. See Figure 2-10b. Thin, avocado-color gossan and fusain horizontal layers are also observed in these figures. In addition, scattered grains of pyrite are present.

2.4.2 Soaked Old Ben Coal

The signal transmitted through 3.5-inch thick Old Ben coal doubled after 5 minutes of soaking in water, increased by a factor of four after two hours of soaking in water, and also increased by a factor of four after 5 minutes of soaking in Thinzit solvent. The fact that the acoustic transmission increased only slightly can be attributed to the presence of impurity layers which are unaffected by soaking.

2.4.3 As-Received Clinchfield Coal

Samples of the Clinchfield coal were badly broken when received and no large slabs were available for testing. This coal was easily crushable, had some fusain layers but low sulfur and ash content, and was free from any observable foreign layers. Clinchfield coal pieces showed very poor acoustic transmission. With a 1600-volt impulse excitation, the signal transmitted through 3.5-inch thick coal was not observable above background noise.

2.4.4 Soaked Clinchfield Coal

Soaking slightly enhanced the transmission through Clinchfield coal pieces; however, no quantitative comparison could be made since no signals could be detected for the dry samples.

2.4.5 As-Received Bruceton Coal

Samples from Bruceton, Pennsylvania were obtained and tested. Visual observation showed the absence of impurity layers. The coal slabs appeared very hard, but possessed some fusain layers. The amplitude of a 150 kHz single-cycle sine wave transmitted through a 1.5-inch thick slab decreased more than 120 dB.

2.4.6 Soaked Bruceton Coal

The signal transmitted through the same Bruceton coal piece increased by a factor of 20 after 5 minutes of soaking in water

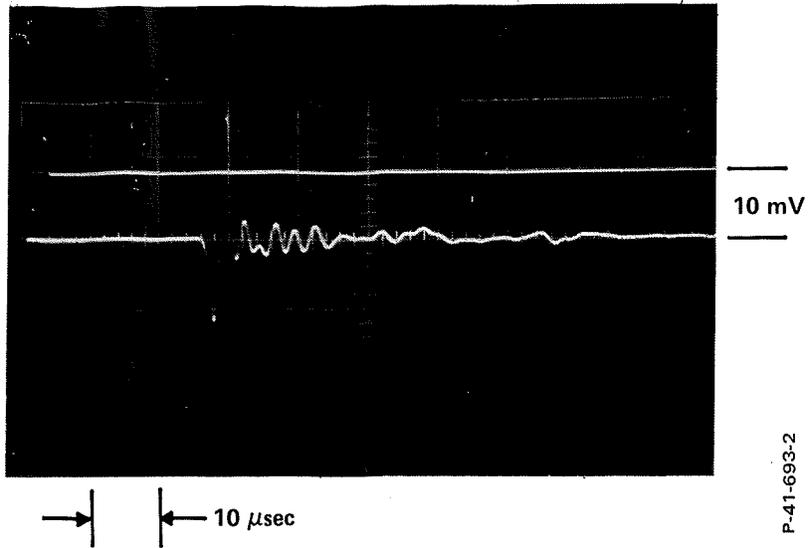
and by a factor of 200 after 5 minutes of soaking in Thinzit. For the 5 minute solvent-soaked coal piece, the transmitted signal was down 80 dB, or 20 dB/in at a frequency of 300 kHz.

2.4.7 As-Received Kentucky Coal

Most of the initial lab work was done on large slabs of coal known as Kentucky coal which were obtained locally. This type of coal has no visible impurity layers and it is very hard. The mine from which this coal originated is unknown, but it is known that the coal was excavated by blasting which has produced visible cracks in the coal. The one-way loss at 300 kHz single-cycle-sine excitation in 2.3-inch thick Kentucky coal is only 77 dB, of which 50 dB is due to transduction and beam spreading. This indicates an effective loss of 10 dB/inch which is very close to the estimated 6 dB/inch acoustic absorption. Figure 2-11a shows a typical signal transmitted through 2.3-inch thick Kentucky coal when excited with 300 kHz, 100-volt peak, single-cycle sine pulses. Figure 2-11b shows the signal reflected from the back face of the coal slab when the back side of the coal was in contact with a 1-1/2-inch thick concrete slab to simulate an overburden material.

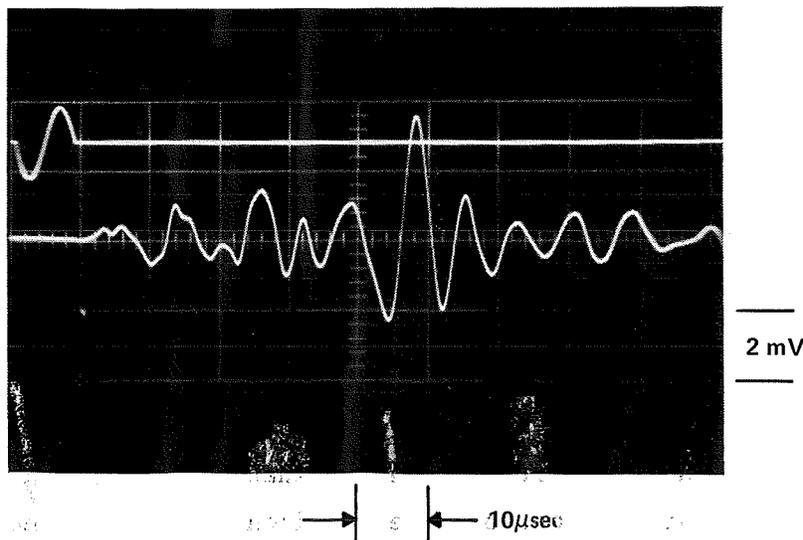
2.4.8 Soaked Kentucky Coal

The most dramatic effect of soaking was observed in a 4.5-inch thick Kentucky coal which was soaked overnight in water containing small amounts of liquid soap to reduce the water surface tension. The excitation was a 150 kHz single-cycle sine pulse of 100-volt peak. Figure 2-12a shows a strong reflection originating at 1-1/2 divisions corresponding to a visually observable 1.5-inch deep crack and another reflection originating at 4-1/2 divisions corresponding to the bottom coal-air interface. Figure 2-12b shows the same 1.5-inch deep crack reflection, but the amplitude of the bottom reflection has decreased, because in this case water was in contact with the coal bottom and reduced the coefficient of reflection. Figures 2-12c and d show, in addition to the 1.5-inch deep crack reflection, the bottom coal-water



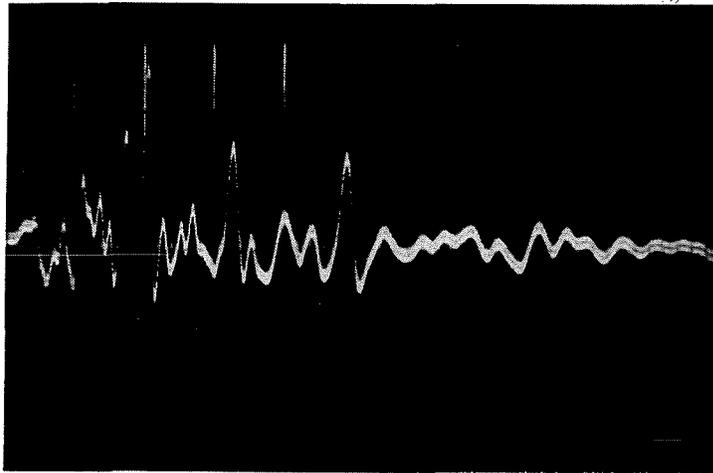
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a) Transmission Thru 2.3" Kentucky Coal Slab.



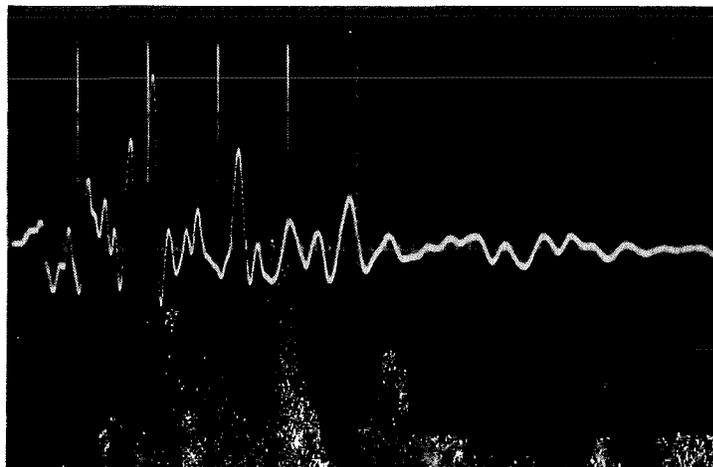
b) Reflection From Coal-Concrete Interface. Coal 2.3" Kentucky Coal Slab.

Figure 2.11 - Transmission and Reflection of 2.3 Inch - Kentucky Coal



(a) COAL OUT OF WATER

↑ CRACK REFLECTION ↑ COAL BOTTOM REFLECTION



(b) COAL IN CONTACT WITH WATER

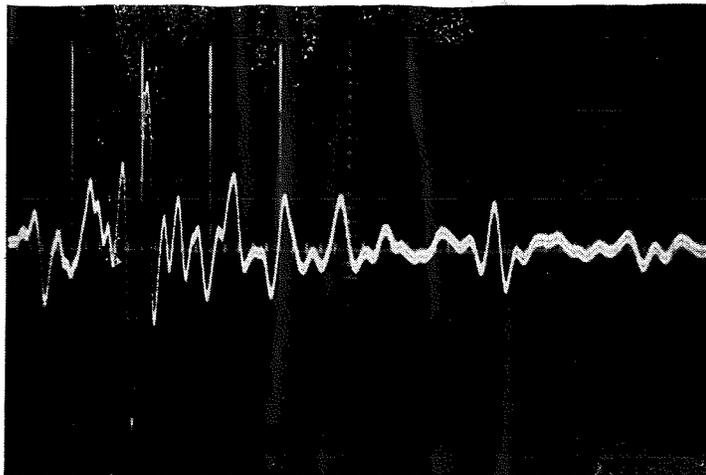
↑ CRACK REFLECTION ↑ COAL BOTTOM ← 20 μsec

2 mV

Figure 2-12 - Effect of S.

from Coal (1 of 2)

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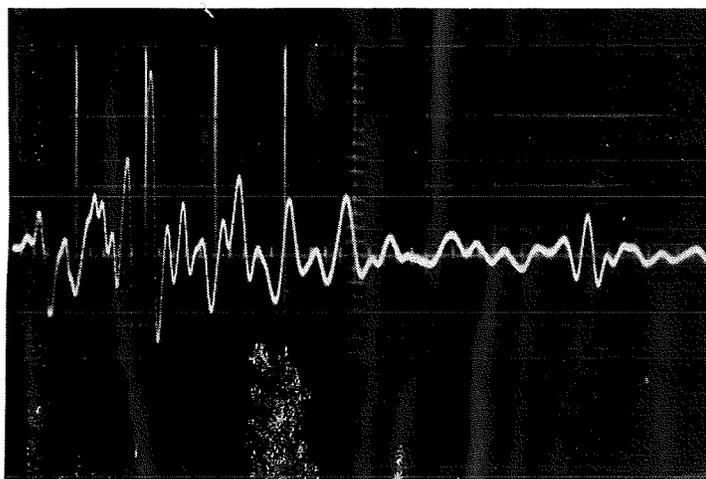


(c) COAL SUBMERGED IN WATER
1.2 INCHES FROM BOTTOM OF
WATER CONTAINER

↑
CRACK REFLECTION

↑
COAL BOTTOM REFLECTION

↑
CONTAINER BOTTOM REFLECTION



(d) COAL SUBMERGED IN WATER
2 INCHES FROM BOTTOM OF
WATER CONTAINER

↑
CRACK REFLECTION

↑
COAL BOTTOM REFLECTION

↑
CONTAINER BOTTOM REFLECTION

20 μsec

2 mV

Figure 2-12 - Effect of Coal Position on Reflections from Coal (2 of 2)

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interface reflection, other reflections originating at 6-1/2 and 7-1/2 divisions, respectively. These latter reflections were due to signals reflected from the bottom of the water container, as the coal slab was displaced vertically in the container.

2.5 SUMMARY

Tests on laboratory samples of coal indicate that attenuation losses through the coal are compounded by impurity layers and cracks in the coal samples. The existence of and types of impurity layers along with the degree of coal hardness varied considerably from sample to sample. At this point, it was recognized that the structure of coal itself might present difficulties in measuring coal thickness. Therefore, detailed design of further hardware was suspended until an underground field test could be made to compare the structure of coal *in situ* with that of laboratory samples.

SECTION 3

FIELD TEST IN OLD BEN MINE

3.1 GENERAL

The experimental underground field test performed at the Old Ben Coal Corporation Mine #24 is described in this section. The primary purpose of the field test was to evaluate the effectiveness of using acoustic reflection techniques to measure coal layer thickness *in situ* and to determine whether further development of the method is justified. Specific objectives of the test were to determine whether cracks are inherent in freshly mined coal and to determine what effects cracks and foreign layers in the coal have on the detected acoustic signal.

3.2 TEST DESCRIPTION

Various requirements were established in determining the mine site for the field test. These were as follows:

- The mine should be an operating coal mine
- The mine should employ a continuous mining machine
- A fresh coal face should be made available for testing
- Non-permissible commercial equipment should be allowed at the face
- Cooperation of mine personnel would be essential in order to accumulate sufficient test data in a short time

The Old Ben Coal Mine located in southern Illinois satisfied these requirements. The field test began on April 24, 1972 and ended on April 28, 1972.

A fresh coal face was prepared for testing by the continuous boring miner. A sketch of the test site dimensions is shown in Figure 3-1. Note that the thickness of the roof coal along the test tunnel varies from 0" to 13". Acoustic reflection measurements were taken at the five test positions shown in Figure 3-2. These positions included both unfinished rough coal surfaces and finished coal surfaces.

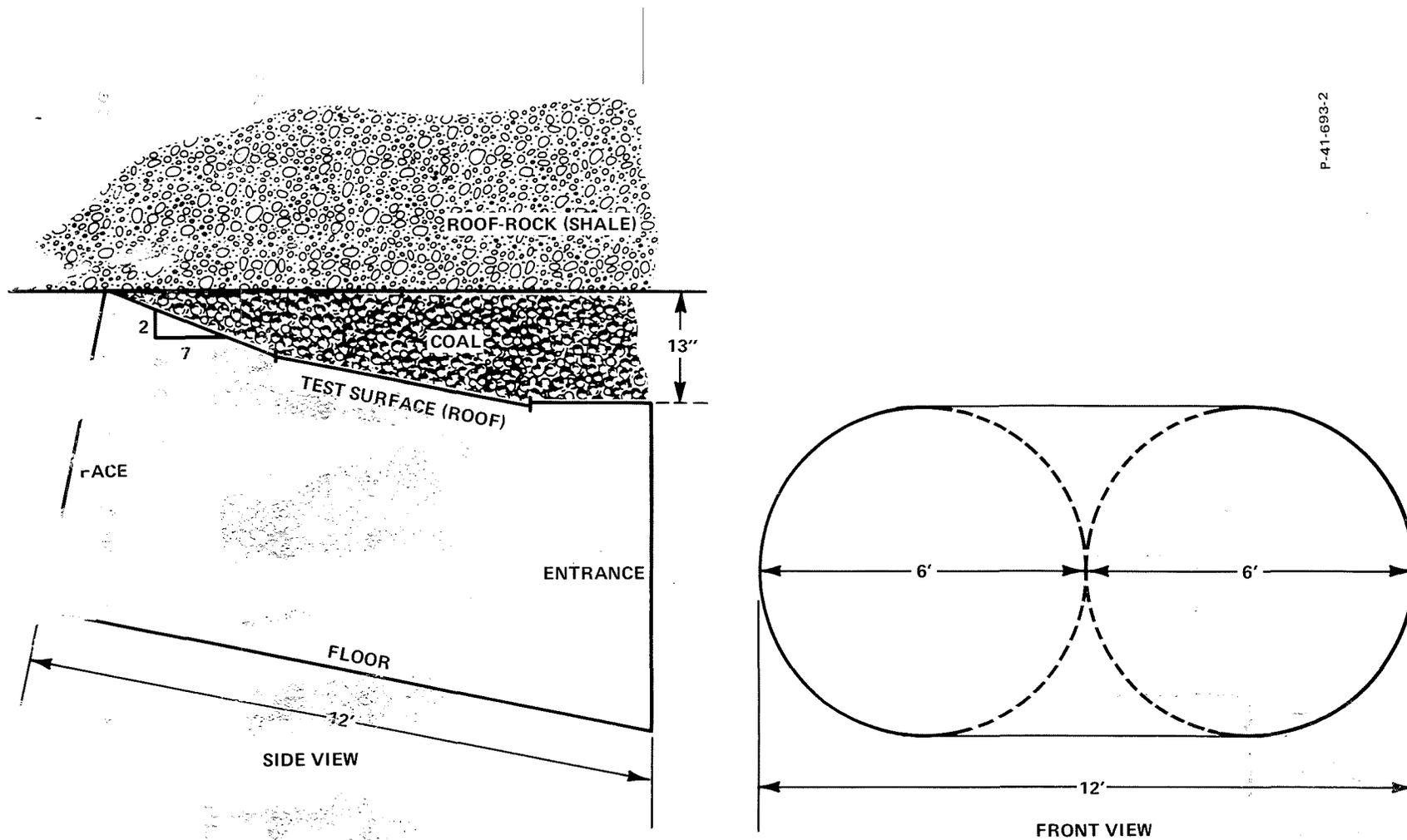
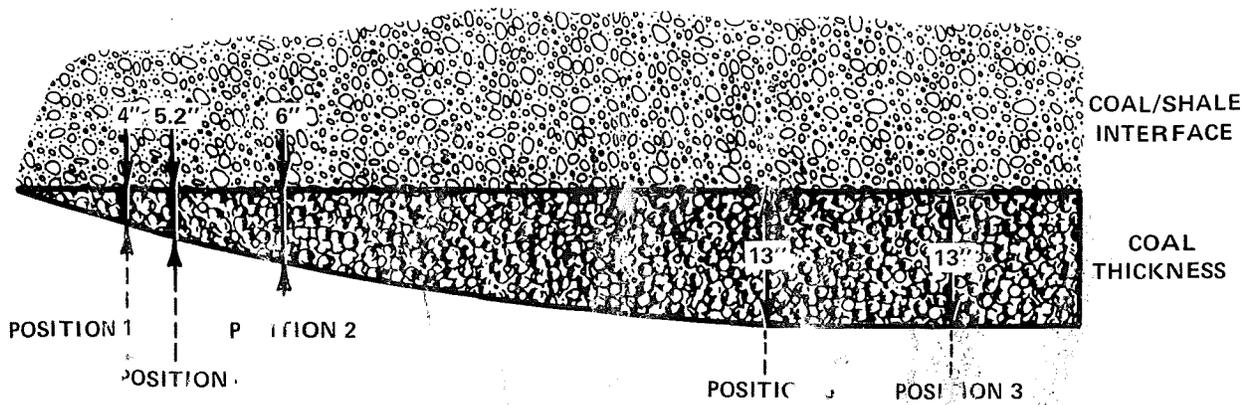


Figure 3-1 - Fresh-Face Test Site at Old Ben Mine

Table 3-1 - Conditions at Test Points During Data Accumulation

| | Transducer-To-Coal Coupling | | |
|------------------------|-----------------------------|--------|--------|
| | | Water | Grease |
| | | COULGH | |
| Coal Surface Condition | S | 1 | 1 |
| | M | | |
| | O | | 2 |
| | OTH | 4 | 4 |

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Figure 3-1 - Acoustic Reflection Test Points on Roof Test Surface

The unfinished rough surface peaks were knocked off with a chisel leaving surface undulations of less than 0.25 inches. The finished smooth surface was ground down with a belt sander using No. 40 sandpaper. Separate transmit/receive transducers were coupled to the coal with either water or grease. Table 3-1 shows the coal surface condition and transducer-to-coal coupling used at the five test points.

Commercial test equipment was used at the coal mine. Figure 2-5 depicts the type of instrumentation used and the interconnections. The F34 function generator put out a single-cycle sine wave of $\pm 10V$ amplitude each time it was triggered by the 214A pulsed generator. The sine wave frequency was varied from 300 kHz down to 20 kHz. The pulsed generator repetition rate was set at 1 kHz. The function generator sine wave was amplified by 10 in the Krohn-Hite DCA-50R high-voltage amplifier to give $\pm 100V$ peaks. This signal drove the Automation Industries J302 transducer, which was either water- or grease-coupled to the coal surface. Adjacent and close to the transmit transducer was an identical receive transducer similarly coupled to the coal surface. The output of the receive transducer was amplified by a Hewlett-Packard wide-band amplifier Model 466A, having a voltage gain of 100. The amplified received signal was then filtered by a Krohn-Hite Model 3202 filter. The filter served two purposes: namely, to reduce 60 Hz pickup, and to reduce high-frequency electronic clutter superimposed on the received signal. For the field test, the filter was primarily operated as a high-pass 48 dB/octave filter, or as a 24 dB/octave band-pass filter. The mode of operation was Butterworth rather than RC. As a minimum band-pass filter, the Model 3202 has a 6 dB insertion loss at the center frequency. The output of the filter was displayed on the Tektronix 454 oscilloscope. The received signal waveforms were photographed with a scope camera. The two-channel capacity of the oscilloscope allowed both the Krohn-Hite amplifier output and the Hewlett-Packard amplifier output to be displayed on the oscilloscope screen. The oscilloscope was triggered with a signal from the function generator. The relative

3.3 DATA COMPILATION

Basic return signal data were recorded on Polaroid oscilloscope pictures. Related information, such as transmitted signal frequency, filter setting, scope sweep speed, surface condition (rough or smooth), transducer-to-surface coupling (water or grease), and other pertinent details were recorded in a log book. This information has been tabulated in Tables 3-2 through 3-6. Included in the tables are signals reflected from various coal depths and their respective amplitudes. Coal depths were measured from the transducer-to-coal interface. The signal amplitudes was measured as the first peak of the signal (see Figure 3-3).

Data were recorded for five test positions in terms of the following variable parameters: transmitted signal frequency; high-pass (HP) or low-pass (LP) filter mode and corner frequencies; condition of the coal surface either rough or smooth; water or grease transducer-to-coal coupling, and slight variations in transducer placement within nominal position.

Position 1, for which data are presented in Table 3-2, had a coal/shale interface at a coal depth of 4" from the roof surface. Photos 1 through 4 for this position were taken about 2.5 hours after the coal had been mined on April 25; photos 5 through 21 were taken on April 26;

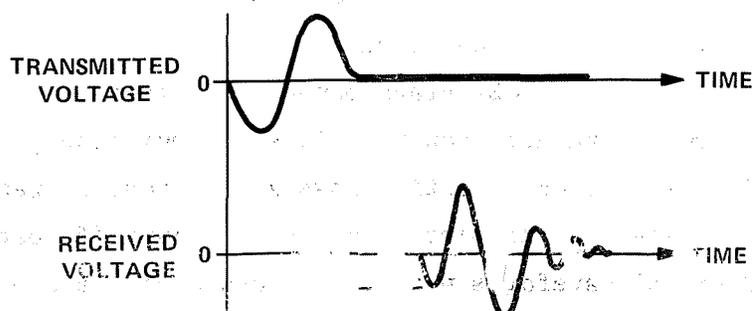


Table 3-2 - Position No. 1 Coal Seam Thickness: 4 Inches

| Photo No. | Freq. (kHz) | Reflective Surface | | | | Filter | | Sweep Speed (μsec/cm) | Surface Condition | Coupling | Remarks | |
|-----------|-------------|--------------------|-----------|-------------|-----------|----------|----------|-----------------------|-------------------|----------|--|--|
| | | Depth (in.) | Ampl (mV) | Depth (in.) | Ampl (mV) | HP (kHz) | BP (kHz) | | | | | |
| 1 | 300 | 2.4* | 0.05 | | | 60 | | 10 | Rough | Grease | • Face was 2-1/2 hrs. old at start of tests on April 25 (photos 1-4) | |
| 2 | 200 | 2.0 | 0.04 | 5.0 | 0.05 | 150 | | 20 | Rough | Grease | | |
| | | 7.0* | 0.05 | 8.0* | 0.08 | | | | | | | |
| 3 | 150 | 0.8 | 0.15 | 5.0 | - | 150 | | 20 | Rough | Grease | • All HP filter attenuation settings on photos 1-24 are 24 db/oct. | |
| 4 | 300 | 2.2 | 0.2 | 6.5 | 0.05 | 150 | | 20 | Rough | Grease | | |
| | | 7.5 | 0.04 | | | | | | | | | |
| 5 | 300 | - | - | - | - | 100 | | 10 | Smooth | Water | • Photos 5-21 taken April 26. | |
| 6 | 200 | 0.6 | 0.30 | 2.6* | 0.10 | 100 | | 10 | Smooth | Water | | |
| | | 3.2* | 0.20 | | | | | | | | | |
| 7 | 200 | 0.5 | 0.05 | 1.5 | 0.80 | 100 | | 10 | Smooth | Water | • Water coupling refilled | |
| | | 3.5* | 0.15 | | | | | | | | | |
| 8 | 300 | 0.5* | 0.10 | 0.8 | 0.25 | 100 | | 10 | Smooth | Water | | |
| | | 1.2 | 0.40 | 2.5 | 0.40 | | | | | | | |
| | | 3.4 | 0.15 | | | | | | | | | |
| 9 | 300 | 0.6* | 0.04 | 0.8 | 0.08 | 100 | | 10 | Smooth | Grease | | |
| | | 1.5 | 0.05 | 2.9* | 0.04 | | | | | | | |
| 10 | 200 | 0.5* | 0.08 | 1.1 | 0.04 | 100 | | 10 | Smooth | Grease | | |
| | | 1.8 | 0.04 | 2.6* | 0.04 | | | | | | | |
| | | 3.2 | 0.20 | 3.7 | 0.18 | | | | | | | |
| 11 | 150 | 0.6 | 0.06 | 1.0 | 0.10 | 100 | | 10 | Smooth | Grease | | |
| | | 1.8 | 0.08 | 2.6* | 0.10 | | | | | | | |
| 12 | 300 | 0.7 | 0.20 | 1.0 | - | 100 | | 10 | Smooth | Grease | | |
| | | 1.6 | 0.10 | | | | | | | | | |
| 13 | 200 | 0.6 | 0.10 | 1.6 | 0.10 | 100 | | 10 | Smooth | Grease | | |
| | | 2.9* | 0.30 | | | | | | | | | |
| 14 | 300 | 0.7 | 0.15 | 1.25 | 0.08 | 100 | | 10 | Smooth | Grease | | |
| 15 | 300 | 0.6* | 0.10 | 1.0 | 0.10 | 100 | | 10 | Smooth | Grease | • Transducers interchanged and moved over 1-1/4 inch. | |
| | | 1.9 | 0.20 | 2.6 | 0.40 | | | | | | | |
| | | 3.9 | 0.40 | | | | | | | | | |
| 16 | 200 | 0.6* | 0.05 | 1.0 | 0.10 | 100 | | 10 | Smooth | Grease | | |
| | | 1.9 | 0.40 | 2.8 | 0.20 | | | | | | | |
| | | 3.9 | 0.30 | | | | | | | | | |
| 18 | 300 | 0.7* | 0.10 | 1.0* | 0.10 | 50 | | 10 | Smooth | Grease | | |
| | | 1.9 | 0.20 | 2.6 | 0.20 | | | | | | | |
| 19 | 300 | - | - | - | - | - | | 10 | Smooth | Grease | • Transceiver mode. | |
| 20 | 300 | - | - | - | - | - | | 10 | Smooth | Grease | • Transceiver mode. | |
| 21 | 300 | 1.4 | 0.02 | | | 50 | | 10 | Rough | Grease | • Separate transmit/receive transducers | |
| 22 | 300 | 0.7* | 0.10 | 1.0* | 0.10 | 100 | | 10 | Rough | Grease | • Photos 22-24 taken April 27. | |
| | | 1.9 | 0.20 | 2.6 | 0.20 | | | | | | | |
| 23 | 300 | 0.7* | 0.10 | 1.0* | 0.10 | 50 | | 10 | Smooth | Grease | | |
| | | 1.9 | 0.20 | 2.6 | 0.20 | | | | | | | |
| 24 | 300 | 0.6* | 0.10 | 1.7 | - | 50 | | 10 | Smooth | Grease | | |
| | | 2.0 | 0.20 | 2.6 | 0.40 | | | | | | | |
| 69 | 300 | 0.5* | - | 0.7 | - | 50 | | 10 | Smooth | Grease | • Retest on April 28 | |
| | | 1.7* | 0.70 | 2.0 | - | | | | | | | |
| | | 2.4* | - | 2.6* | - | | | | | | | |
| 70 | 200 | 0.8 | - | 1.5 | - | 50 | | 20 | Smooth | Grease | | |
| | | 2.8 | - | 4.0 | 0.40 | | | | | | | |
| 71 | 300 | 0.7 | - | 1.1 | - | 50 | | 20 | Smooth | Grease | • Moved 1/8 inch. | |
| | | 1.8 | 0.20 | 3.0 | - | | | | | | | |
| 72 | 200 | 0.7 | - | 1.4 | - | 50 | | 20 | Smooth | Grease | | |
| | | 2.6 | - | | - | | | | | | | |
| 73 | 20 | 1.5 | - | | | | 20 | 50 | Smooth | Grease | | |
| 74 | 300 | 0.9* | - | 1.4* | - | 50 | | 10 | Smooth | Grease | • Moved 1/8 inch. | |
| | | 2.0 | 1.2 | 3.0* | - | | | | | | | |
| 75 | 300 | 1.0 | - | 1.5* | - | 300 | | 10 | Smooth | Grease | | |
| | | 2.0 | 0.4 | 3.0 | - | | | | | | | |
| 76 | 20 | 1.5 | - | 5.0* | - | | 20 | 50 | Smooth | Grease | | |
| | | 12.0* | - | | - | | | | | | | |
| 77 | 300 | 0.5 | - | 0.8 | - | 50 | | 20 | Smooth | Grease | • Separate transducers by 1/8 inch. | |
| | | 1.4 | - | 2.8* | - | | | | | | | |
| | | 3.0* | - | | - | | | | | | | |
| 78 | 300 | 0.5* | - | 1.0* | - | 50 | | 20 | Smooth | Grease | • Moved 1/8 inch. | |
| | | 1.5 | - | 1.7* | - | | | | | | | |
| | | 2.2 | - | 3.0* | - | | | | | | | |
| 79 | 300 | 0.7 | - | 1.0 | - | 50 | | 20 | Smooth | Grease | • Moved 1/8 inch. | |
| | | 1.2 | - | 1.5* | - | | | | | | | |
| | | 1.8 | 0.3 | 2.4 | - | | | | | | | |
| | | 3.2 | - | 4.5* | - | | | | | | | |
| 80 | 300 | 1.4 | - | 2.1 | - | 50 | | 20 | Smooth | Grease | • Moved 1/8 inch. | |
| | | 2.6 | - | 3.5* | - | | | | | | | |
| | | 3.8 | 0.50 | 4.4 | - | | | | | | | |

* Asterisk indicates weak signal-to-noise ratio.

photos 22 through 24 on April 27; photos 69 through 80 were taken April 28 as a retest of the position three days after mining. The HP filter slope was set at 24 dB/octave for photos 1 to 24 and at 48 dB/octave for the remaining photos.

The asterisk associated with the reflective surface depths indicate weak signal-to-noise ratio. In this case, the noise is those undesired spurious signals in the immediate vicinity of the reflected signal. Photos 19 and 20 were taken using the transceiver mode of operation. Because the reflected signals were of lesser amplitude than the reflection off the transducer backing, no return signals could be observed. There was no further attempt to use the transceiver in the coal mine.

Figure 3-4 shows two photographs of actual data recorded at position 1. The photograph numbers are 10 and 15. The approximate relationship between scope sweep time and coal thickness is 20 μ sec/inch. Photo 10 shows reflected signals from 0.5, 1.1, 1.8, 2.6, 3.2, and 3.7 inches of coal depth. The 3.7" signal represents the coal/shale interface. Photo 15 shows reflected signals from coal depths of 0.6, 1, 1.9, 2.6, and 3.9 inches. The 1.9" reflection is relatively large, and the coal/shale interface can be recognized from the 3.9" signal. Another photo, #70, taken later in the experiment, showed signals at coal depths of 0.8, 1.5, 2.8, and 4 inches. The signal-to-noise ratio of the 4" coal/shale signal was relatively large.

Table 3-3 gives the data for position No. 2 taken April 27th. The coal/shale interface was at a depth of 6". The surface was sanded smooth with the belt sander, and grease coupling of the transducers was used. Most of the measurements were made at 300 kHz, and all used the filter at 50 kHz HP with 48 dB/octave attenuation slope. In photos 26, 28, and 29, no evidence of the 6" coal/shale interface was observable. It was anticipated that possible horizontal cracks at 0.5" and 2" precluded any signal return from the 6" interface. As an attempt to overcome this possibility, a small hole 1/4" in diameter, equally distant from the two transducers, was drilled up through the coal. Water was

Table 3-3 - Position No. 2 Coal Seam Thickness: 6 Inches

| Photo No. | Freq. (kHz) | Reflective Surface | | | | Filter | | Sweep Speed (μ sec/cm) | Surface Condition | Coupling | Remarks |
|-----------|-------------|--------------------|-----------|-------------|-----------|----------|----------|-----------------------------|-------------------|----------|--|
| | | Depth (in.) | Ampl (mV) | Depth (in.) | Ampl (mV) | HP (kHz) | BP (kHz) | | | | |
| 25 | 200 | - | - | - | - | 50 | | 5 | Smooth | Grease | • Drive signal |
| 26 | 200 | 0.5 | - | 2.0* | - | 50 | | 20 | Smooth | Grease | |
| 27 | 300 | - | - | - | - | 50 | | 5 | Smooth | Grease | • Drive signal |
| 28 | 300 | 0.5 | - | - | - | 50 | | 20 | Smooth | Grease | |
| 29 | 300 | - | - | - | - | 50 | | 20 | Smooth | Grease | • Receiver moved 1/2 inch. |
| 31 | 300 | | | | | 50 | | 20 | Smooth | Grease | • Before water injection |
| 32 | 300 | 0.5 | - | 0.8 | - | 50 | | 10 | Smooth | Grease | • Hole drilled between transducers for water injection. Start water injection on photo 32. |
| | | 1.0 | - | 1.3 | - | | | | | | |
| 33 | 300 | - | - | - | - | 50 | | 20 | Smooth | Grease | • 11 min. after water injection |
| | | 0.5 | - | 2.0* | - | | | | | | |
| 35 | 300 | 0.5 | - | 2.0* | - | 50 | | 10 | Smooth | Grease | • 10 min. after solvent injection |
| 36 | 300 | | | | | 50 | | 20 | Smooth | Grease | • 10 min. after solvent injection |
| 37 | 300 | 0.5* | - | 2.0 | 0.06 | 50 | | 10 | Smooth | Grease | • 30 min. after solvent injection |
| 38 | 300 | 0.5* | - | 4.0* | - | 50 | | 20 | Smooth | Grease | • 30 min. after solvent injection |

* Asterisk indicates weak signal-to-noise ratio.

injected into this hole with the hope of filling in any horizontal cracks. Photo 31 was taken as a reference prior to water injection, and photos 32 to 34 were taken after water injection. The results were negative; no return signals appeared from the 6" interface. Since Thinzit solvent (mixture of isopropanol, ethanol, and methanol) has a lower surface tension than water, it was injected into the hole. Photos 35 to 38, taken after the solvent injection, revealed no obvious sign of the 6" interface. These tests indicated that cracks either were not present or were not being filled with the liquid.

Data for position 3 taken April 27 are shown in Table 3-4. The coal seam thickness at this site was estimated at 13", and a pyrite (iron disulfide) boundary was visible at a depth of 3" from the roof surface. Measurements at this position were primarily intended to determine whether a signal would be reflected off the coal-to-iron disulfide interface. The coal surface was left in its unfinished state. It was not as smooth as the sanded surfaces; however, neither was it excessively rough. Photos 40, 42, 43 did show a reflection from the iron-disulfide boundary. Figure 3-5 shows an actual photo (#42) taken at position 3. Signal reflections appear from coal depths of 0.5, 1.8, 2.8, 4.4, 5.8, and 8 inches.

Table 3-5 exhibits data taken on April 27 for position 4, where the coal seam thickness was 5.2". A number of parameters were varied during these measurements. The signal frequency was varied from 300 kHz down to 20 kHz. Data were taken for the high-pass (HP) and band-pass (BP) filter modes for both rough and smooth surface conditions, and for both grease and water coupling. In some cases, the surface was soaked with water or Thinzit solvent. Photographs 50 and 60 from position 4, are shown in Figure 3-6. Photo 50 at 50 kHz shows a distinct signal from 1.8 inches; however, note that the 5.2" coal/shale interface

Table 3-4 - Position No. 3 Coal Seam Thickness: 13 Inches

| Photo No. | Freq. (kHz) | Reflective Surface | | | | Filter | | Sweep Speed (usec/cm) | Surface Condition | Coupling | Remarks |
|-----------|-------------|--------------------|-----------|-------------|-----------|----------|----------|-----------------------|-------------------|----------|---------------------------|
| | | Depth (in.) | Ampl (mV) | Depth (in.) | Ampl (mV) | HP (kHz) | BP (kHz) | | | | |
| 40 | 50 | 0.5 | - | | | | 50 | 20 | Rough | Grease | • Coal surface unfinished |
| | 100 | 0.5 | - | 1.5 | - | | 100 | 20 | Rough | Grease | |
| | | 2.8 | - | 5.6 | - | | | | | | |
| 41 | 150 | 1.8 | - | 3.3* | - | | 150 | 20 | Rough | Grease | |
| | | 5.5* | - | | | | | | | | |
| 42 | 200 | 0.5 | - | 1.8 | - | | 200 | 20 | Rough | Grease | |
| | | 2.8 | - | 4.4 | - | | | | | | |
| | | 5.8 | - | 8.0 | - | | | | | | |
| 43 | 300 | 0.5 | - | 1.4 | - | | 300 | 20 | Rough | Grease | |
| | | 2.4* | - | 3.0 | - | | | | | | |
| | | 3.8* | - | 4.6* | - | | | | | | |

* Asterisk indicates weak signal-to-noise ratio.

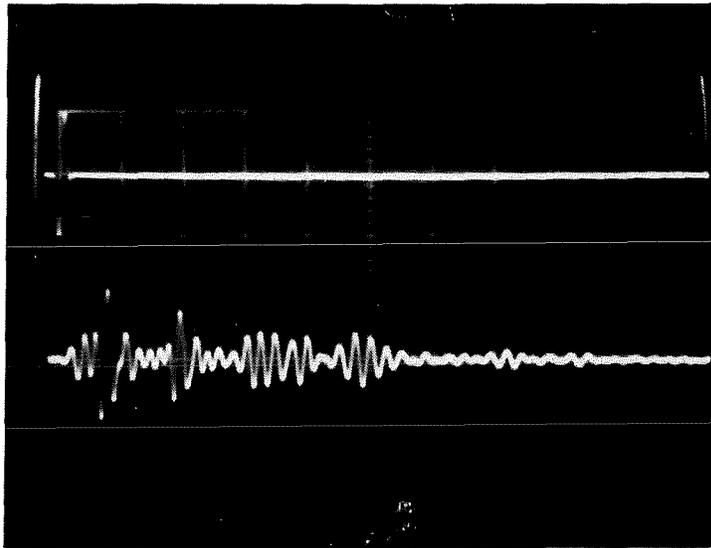


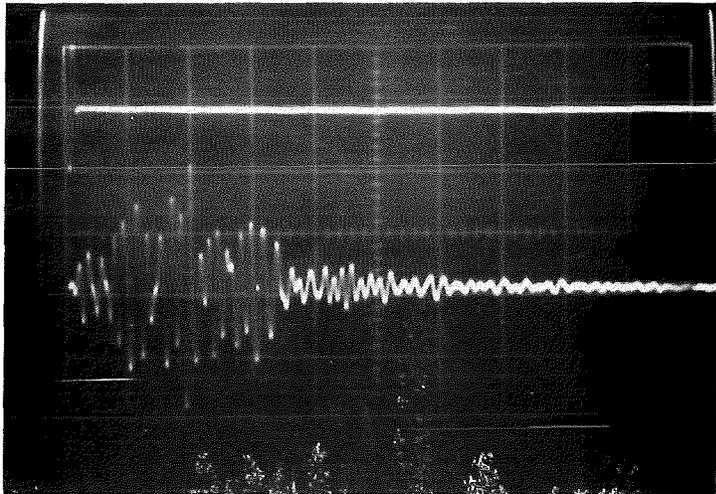
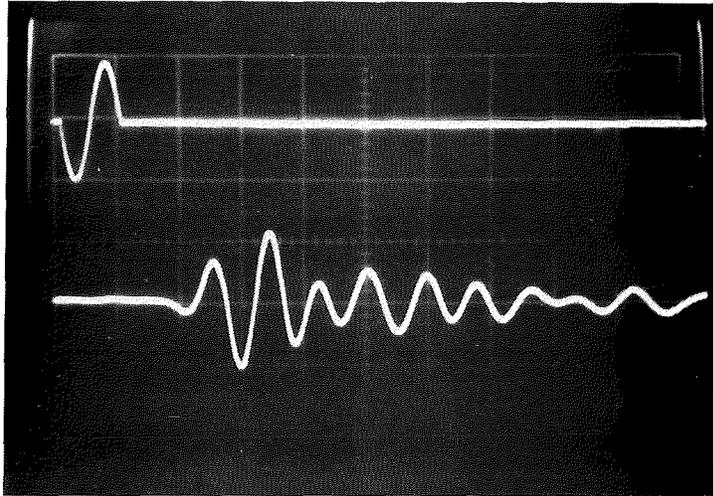
Figure 3-5 - Photograph of Detected Signal From Position 3 at Old Ben

Table 3-5 - Position No. 4 Coal Seam Thickness: 5.2 Inches

| Photo No. | Freq. (kHz) | Reflective Surface | | | | Filter | | Sweep Speed (usec/cm) | Surface Condition | Coupling | Remarks |
|-----------|-------------|--------------------|-----------|-------------|-----------|----------|----------|-----------------------|-------------------|----------|--|
| | | Depth (in.) | Ampl (mV) | Depth (in.) | Ampl (mV) | HP (kHz) | BP (kHz) | | | | |
| 44 | 300 | 0.5 | - | 1.0 | - | 50 | | 20 | Rough | Grease | • Coal surface high spots knocked off with chisel, roughness \approx \pm 1/8 inch. |
| | | 1.2 | - | 2.0 | - | | | | | | |
| | | 4.0* | - | | | | | | | | |
| 45 | 200 | 0.5* | - | 0.8 | - | 50 | | 20 | Rough | Grease | |
| | | 4.2* | - | 5.4 | - | | | | | | |
| | | 6.8 | - | | | | | | | | |
| 46 | 100 | 1.4 | - | | | 20 | | Rough | Grease | | |
| 47 | 50 | 1.2 | - | 3.4* | - | 3 | | 20 | Rough | Grease | |
| 48 | 20 | 3.0 | - | | | 3 | | 50 | Rough | Grease | |
| 49 | 20 | 1.0 | - | 3.5* | - | | 20 | 50 | Rough | Grease | |
| 50 | 50 | 1.8 | - | | | | 50 | 20 | Rough | Grease | |
| 51 | 300 | 1.0 | - | 2.2 | - | 50 | | 20 | Rough | Grease | • Soak surface with water |
| | | 3.8 | - | | | | | | | | |
| 52 | 100 | 1.0* | - | 2.0 | - | 10 | | 20 | Rough | Grease | • Soak surface with water |
| 53 | 20 | 1.5* | - | 4.0 | - | | 20 | 50 | Rough | Grease | • Soak surface with water |
| 54 | 20 | 1.5* | - | 4.0 | - | | 20 | 50 | Smooth | Water | • Alcohol sprayed on surface |
| 55 | 300 | 0.5 | - | 1.5 | - | 50 | | 20 | Smooth | Water | • Alcohol sprayed on surface |
| | | 2.5 | - | 3.8 | - | | | | | | |
| | | 4.4* | - | 5.2* | - | | | | | | |
| 56 | 150 | 0.6* | - | 1.0* | - | 50 | | 20 | Smooth | Water | • Alcohol sprayed on surface |
| | | 1.4 | - | 2.1* | - | | | | | | |
| | | 4.1 | - | | | | | | | | |
| 57 | 150 | 1.2* | - | 2.0* | - | | 150 | 20 | Smooth | Water | • Alcohol sprayed on surface |
| 58 | 300 | 0.5 | - | 1.2 | - | 50 | | 20 | Smooth | Grease | |
| | | 1.6 | - | 2.0* | - | | | | | | |
| | | 2.6 | - | 2.7 | - | | | | | | |
| | | 5.2* | - | | | | | | | | |
| 60 | 300 | 0.5 | - | 0.7 | - | | 300 | 20 | Smooth | Grease | |
| | | 1.4 | - | 2.0 | - | | | | | | |
| | | 2.6 | - | 3.5 | - | | | | | | |
| | | 4.2* | - | 5.0* | - | | | | | | |
| | | 5.8* | - | | | | | | | | |
| 61 | 150 | 0.6* | - | 2.0 | - | 20 | | 20 | Smooth | Grease | |
| 62 | 50 | 0.6 | - | 3.0* | - | 5 | | 20 | Smooth | Grease | |
| 63 | 20 | 0.2* | - | 2.0 | - | 0.5 | | 20 | Smooth | Grease | |
| | | 6.0* | - | | | | | | | | |
| 64 | 20 | 1.5 | - | | | | 20 | 50 | Smooth | Grease | |
| 65 | 50 | 0.6 | - | 5.2* | - | | 50 | 20 | Smooth | Grease | |
| 66 | 150 | 0.8 | - | 1.6* | - | | | 20 | Smooth | Grease | |
| | | 4.4* | - | 4.6* | - | | | | | | |
| | | 5.6* | - | | | | | | | | |
| 67 | 100 | | - | | - | 50 | | 20 | Smooth | Grease | • Transducers moved slightly; 3 cycle sine wave; signal repetition rate changed from 1 kHz to 5 kHz. |
| 68 | | | 1.8 | - | | 50 | | 20 | Smooth | Grease | |

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the ratio.



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Figure 3-6 - Photographs of Detected Signal From Position 4 at Old Ben

Position 5 was measured on April 28 and the data are shown in Table 3-6. Only three photos were taken, all at low frequencies using BP filtering. The surface condition was unfinished and left in a medium rough condition. Transducer-to-coal coupling was with grease. The coal/shale interface was estimated in the mine at 12". In photo 84 from position 5 (shown in Figure 3-7), the reflection at 240 μ sec represents the 12" coal/shale interface.

3.4 COAL SAMPLE EXTRACTION

Coal samples were taken from positions 1 through 4 on April 28 after all tests had been completed. The location of the transducers at each position was noted with a grease pencil.

Early sample extraction using a concrete core sample cutter resulted in crumbled coal; therefore, this method of extraction was discarded. The following method was then employed. A hand drill and 1/2" diameter masonry bit (or a roof-bolting boring machine) were used to drill a series of holes around the perimeter of the desired coal sample. Then a hammer and a steel chisel were used to cut the coal webbing between the holes.

Samples from positions 1 and 4 were extracted all the way up to the coal/shale boundary. A 2" thick sample was extracted from position 2, but the remaining 4" were too difficult to extract. The sample from position 3 was extracted to the 3" deep iron-disulfide boundary of interest. No attempt was made to remove a sample at position 5 because the 12" depth would have made this task formidable. Photographs of parts of the samples taken from positions 2 and 4 are shown in Figure 2-10(a) and (b), respectively.

The four samples were wrapped very carefully, marked by position, and hand-carried back to the Research Laboratories.

5 DATA AND SAMPLE ANALYSIS

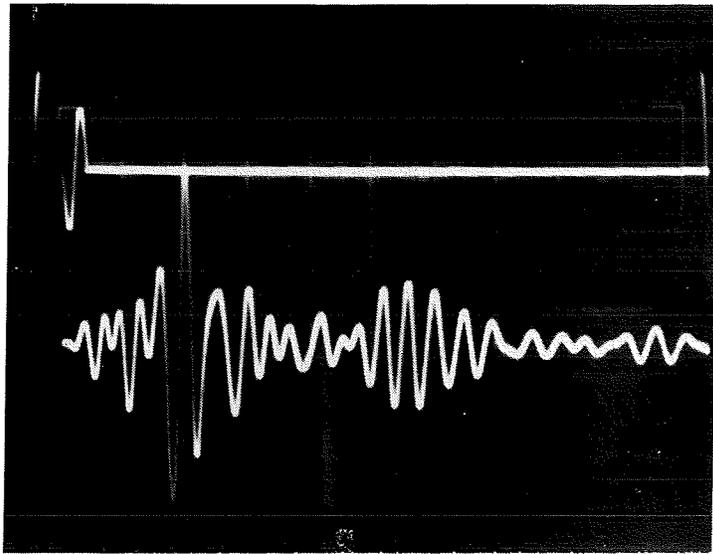
3.5.1 Correlation of Data on Coal Samples

A total of 84 oscillograms were taken for the test positions in the coal. The following parameters were

Table 3-6 - Position No. 5 Coal Seam Thickness: 12 Inches

| Photo No. | Freq. (kHz) | Reflective Surface | | | | Filter | | Sweep Speed (μ sec/cm) | Surface Condition | Coupling | Remarks |
|-----------|-------------|--------------------|-----------|-------------|-----------|----------|----------|-----------------------------|-------------------|----------|--|
| | | Depth (in.) | Ampl (mV) | Depth (in.) | Ampl (mV) | HP (kHz) | BP (kHz) | | | | |
| 83 | 20 | 2.5 | - | | | | 20 | 100 | Rough | Grease | * Coal surface unfinished; left medium rough |
| 84 | 50 | 1.5 | - | 3.0 | - | | 50 | 50 | Rough | Grease | |
| | | 7.0* | - | 12.0 | - | | | | | | |
| 85 | 50 | - | - | - | - | | 50 | 100 | Rough | Grease | |

* Indicates weak signal-to-noise ratio.



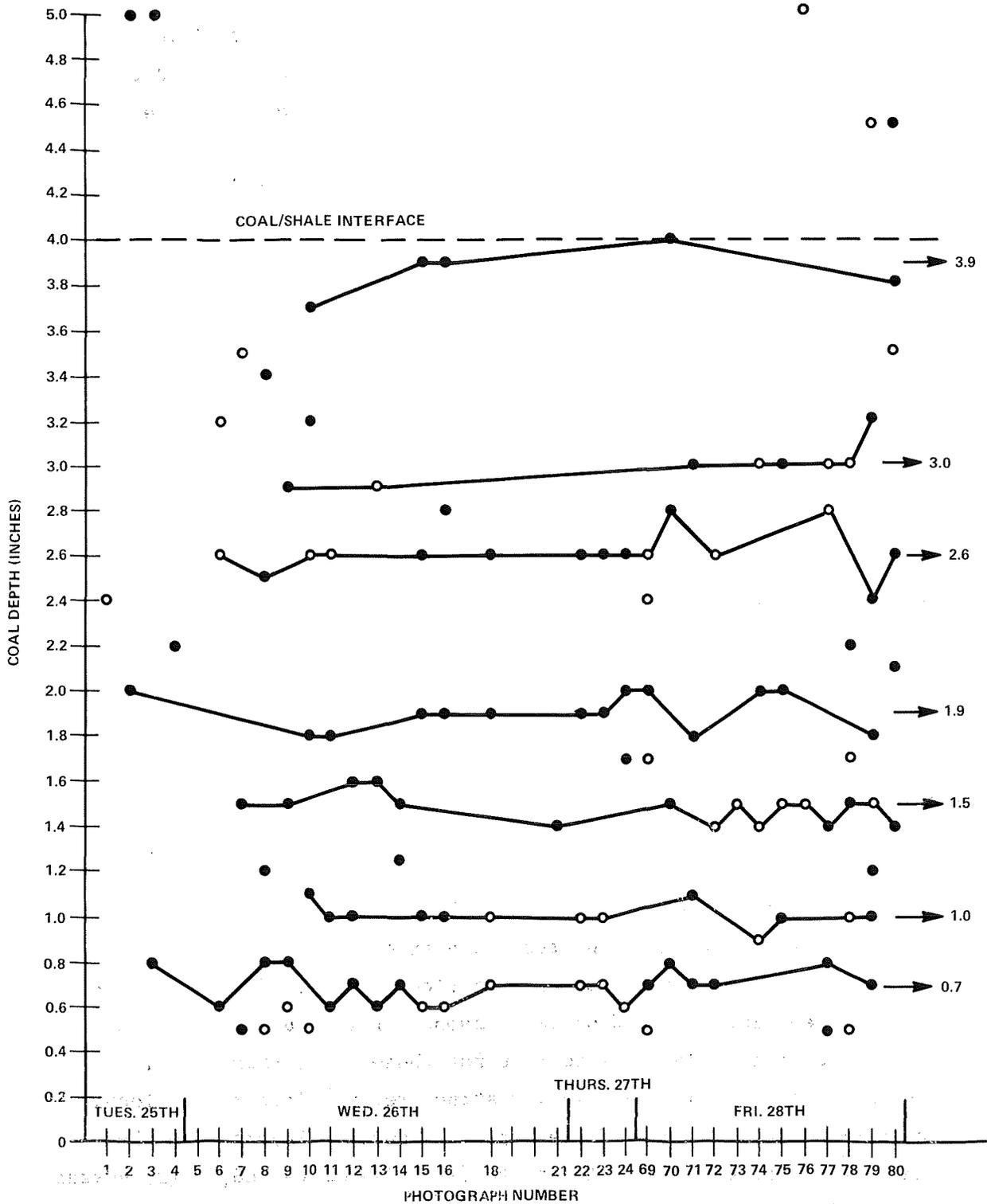
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Figure 3-7 - Photograph of Detected Signal From Position 5 at Old Ben

varied in these photos: transmitted signal frequency, electronic filtering of the received signal, coal surface conditions, transducer-to-coal coupling, water and solvent soaking of coal, and small changes in transducer location within a given position. An overall measure of the correlation of the data, irrespective of the parameter varied, was achieved by plotting all the reflected signals for each position on a single sheet of paper. Reflective interfaces were then determined by the high occurrence of reflected signals from the corresponding coal depths. Such a set of plots is shown in Figures 3-8 through 3-12.

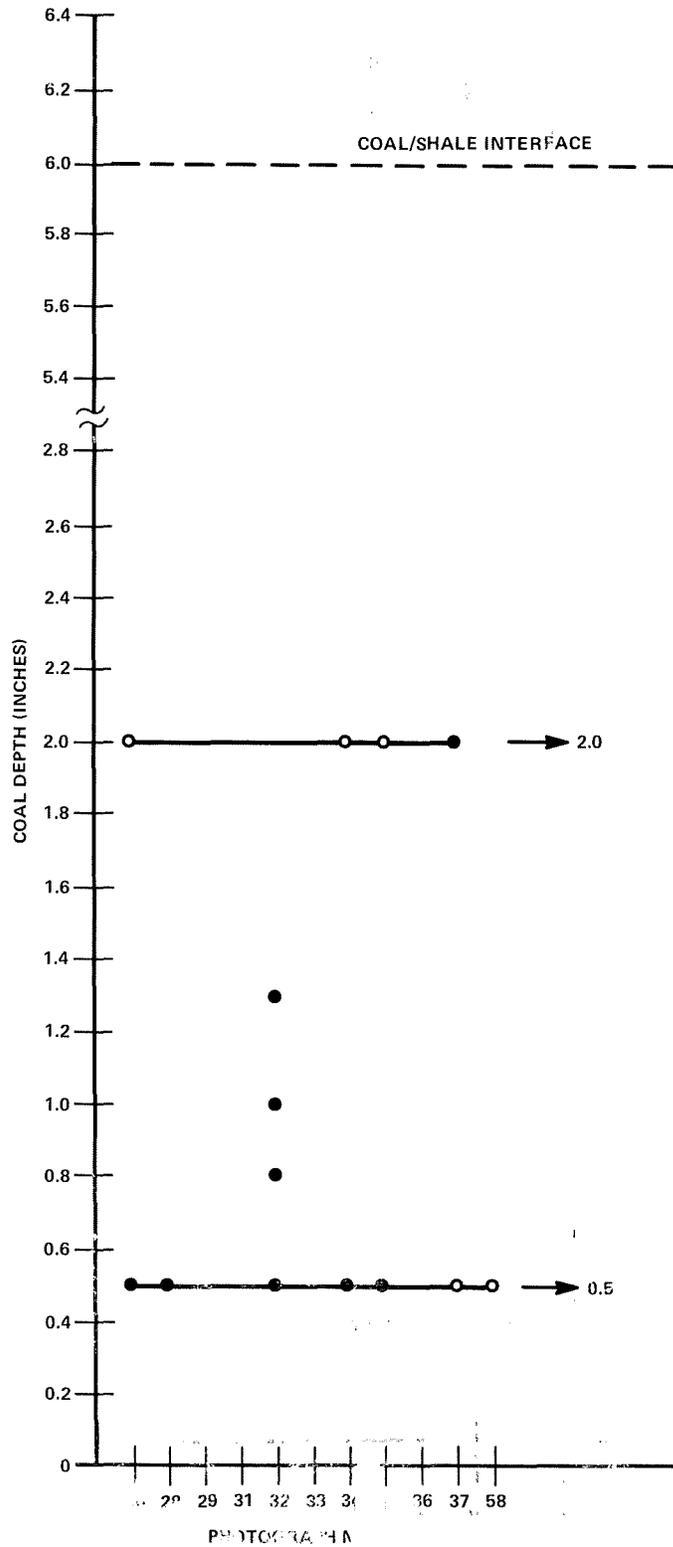
The solid circle data points indicate that the signal amplitude was sufficiently large, compared to adjacent noise, to be easily recognized. The hollow circle points indicate weaker signals with lower signal-to-noise ratio. Lines were drawn between points which appeared to define a nominal depth from which a reflection occurred. The criterion used to determine the allowable data point deviation from the nominal depth was $\pm 20\%$ of the scope sweep speed in $\mu\text{sec}/\text{cm}$, namely, $\pm 2 \mu\text{sec}$ at $10 \mu\text{sec}/\text{cm}$ and $\pm 4 \mu\text{sec}$ at $20 \mu\text{sec}/\text{cm}$. This corresponds to ± 0.1 inch and ± 0.2 inch, respectively. The basis for the $\pm 20\%$ criterion was due to the uncertainty in visually resolving the time sweep on the photographs and the difficulty in extrapolating exactly where the signal started. Signal amplitude was not quantitatively considered in the plots. Figures 3-8 through 3-12 show that the reflective surfaces from all the test data are in good correlation. Table 3-7 lists for each position the coal depth in inches of each reflective surface determined by the correlation of the data.

The four coal samples, positions 1 through 4, were carefully inspected visually to discover reasons for the numerous reflected signals in the data. Possible sources for those reflections were: cracks, impurity layers, the layering structure, multiple reflections, and shear-wave reflections. Three types of impurity layers were observed in the coal samples: (1) pyrite (iron disulfide FeS_2); (2) gossan (non-crystallized pyrite compound); and (3) calcite (crystalline calcium carbonate). These layers can be seen in the photographs of the coal



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Figure 3-8 - Position No. 1 Reflected Signals From Various Coal Depths



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Figure 3-9 - Position of Reference Points at Various Coal Depths

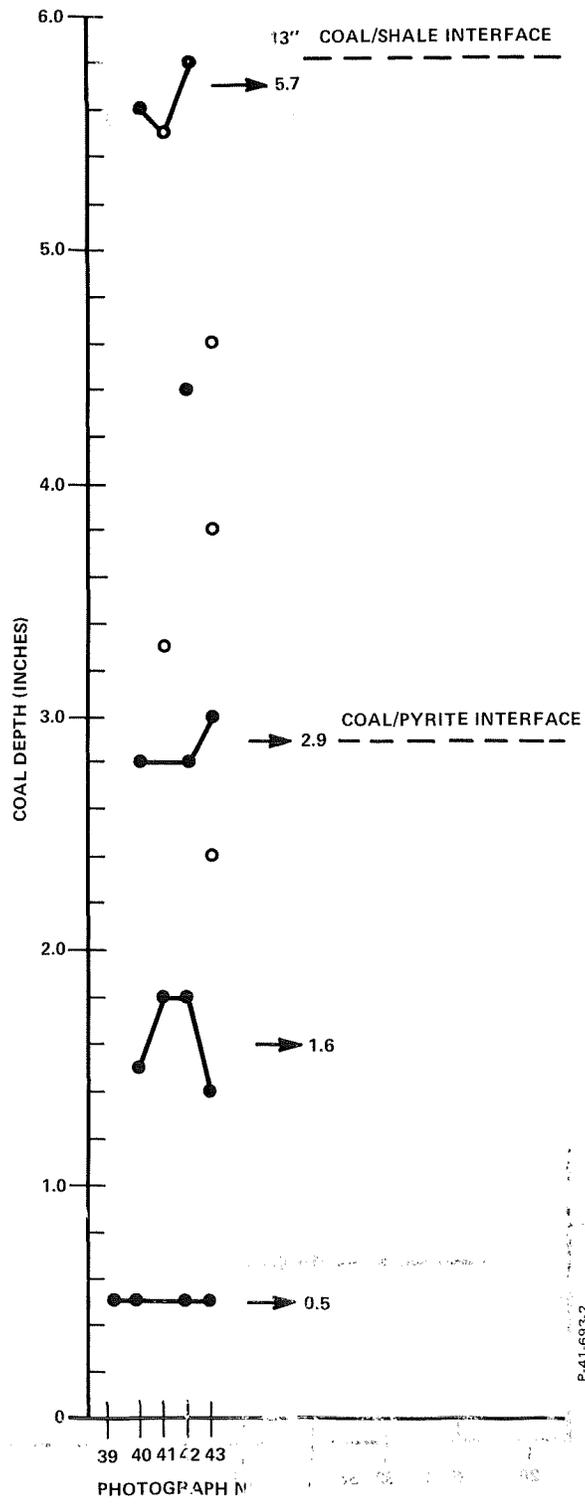


Figure 3-10 - Position N of Signals from Various Coal Depths

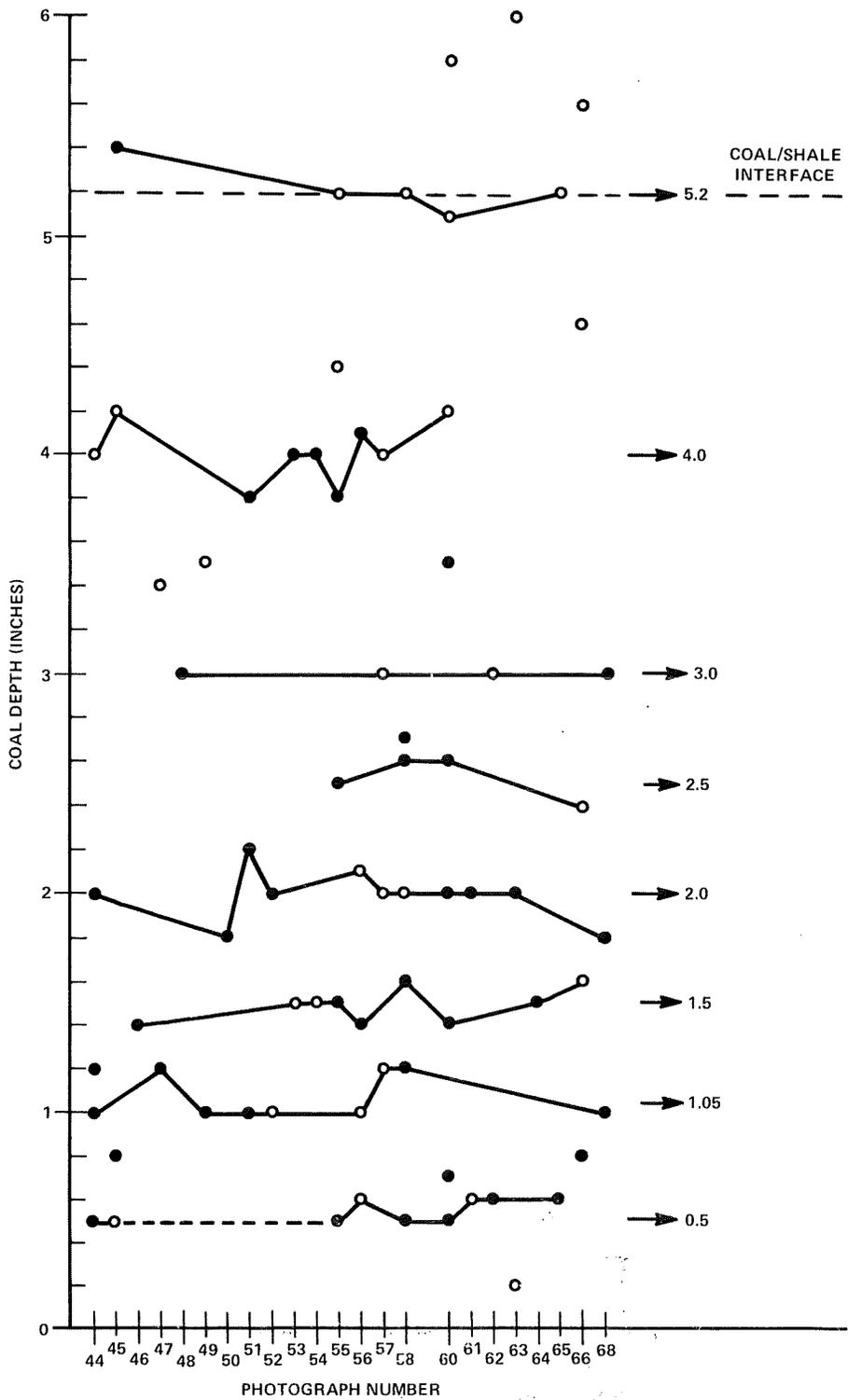


Figure 3-11 - Position No. 4 Reflected Signals From Various Coal Depths

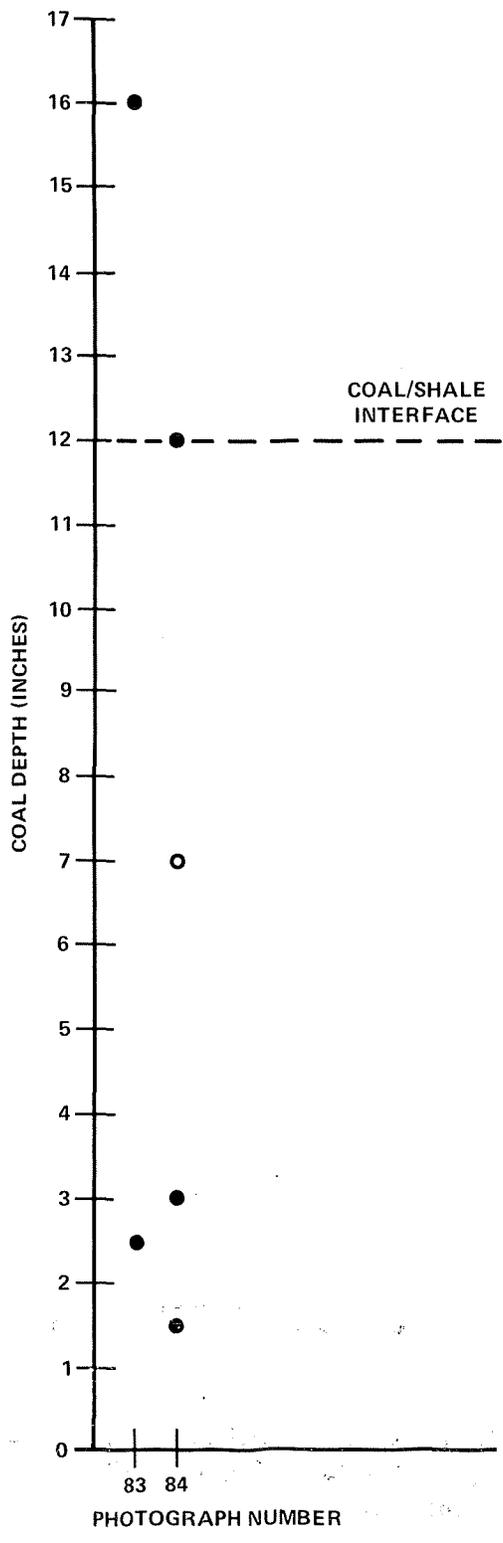


Figure 3-12 - Position No. 5 Reflected Signals From Various Coal Depths

Table 3-7 - Coal Depth (Inches) of Reflective Surface From Experimental Data

| | Position | | | | |
|--|---|-----|-----|------|-----|
| | 1 | 2 | 3 | 4 | 5 |
| | C O A L D E P T H (inches) | 0.7 | 0.5 | 0.5 | 0.5 |
| | 1.0 | 2 | 1.6 | 1.05 | |
| | 1.5 | | 2.9 | 1.5 | |
| | 1.9 | | 5.7 | 2.0 | |
| | 2.6 | | | 2.5 | |
| | 3.0 | | | 3.0 | |
| | 3.9 | | | 4.0 | |
| | | | | 5.2 | |

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Table 3-8 - Visual Analysis of Coal Samples

| Position 1 | | Position 2 | | Position 3 | | Position 4 | |
|---------------------|----------------|---------------------|----------------|---------------------|-----------|---------------------|---------------|
| Coal Depth (inches) | Layer | Coal Depth (inches) | Layer | Coal Depth (inches) | Layer | Coal Depth (inches) | Layer |
| 0.7 | pyrite | 0.5 | pyrite | 2.5 | pyrite | 1.2 | gossan, |
| 1.5 | gossan & crack | 2 | gossan & crack | 3 | soot seam | 2 | maybe pyrite |
| 3 | gossan | | | | | 3 | gossan, maybe |
| 4 | shale | | | | | 4 | gossan, maybe |
| | | | | | | 5.2 | shale |

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Table 3-9 - Correlation of Experimental and Visual Results

| | Position | | | | | | | |
|----------|----------|--------|-----|--------|-----|--------|-----|--------|
| | 1 | | 2 | | 3 | | 4 | |
| | Exp | Visual | Exp | Visual | Exp | Visual | Exp | Visual |
| C | 0.7 | 0.7 | 0.5 | 0.5 | 0.5 | - | 0.5 | - |
| O | 1 | - | 2 | 2 | 1.6 | - | 1.1 | 1.2 |
| A | 1.5 | 1.5 | | | - | 2.5 | 1.5 | - |
| L | 1.9 | - | | | 2.9 | 3 | 2 | |
| D | 2.6 | - | | | | | 2.5 | |
| E | 3 | | | | | | 3 | |
| P | 3.9 | 4 | | | | | 4 | |
| T | | | | | | | | |
| H | | | | | | | | |
| (inches) | | | | | | | 5.2 | |

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samples from positions 2 and 4 shown in Figure 2-10(a) and (b). The pyrite layers ranged between 5 to 20 mils thickness, and ran both parallel and perpendicular to the coal layer structure. The gossan layers ranged between 3 to 7 mils thickness, and ran primarily parallel to the coal layering. The calcite layers were about 20 mils thick and were always observed to be perpendicular to the coal layering. The results of the visual analysis of the four coal samples are tabulated in Table 3-8.

At this point, it was possible to compare the experimental data with the coal samples to determine whether there was any correlation. A convenient comparison is made in Table 3-9. Note that in all cases, except for one in position 3, the visually observed layers corresponded to the experimental data. There were a number of experimentally predicted layers that were not observed on the coal samples. Possible explanations for this are:

- An impurity layer or crack was present, but could not be visually observed
- The experimental signal was the consequence of multiple reflections within the roof coal
- The experimental signal resulted from a shear wave, rather than a longitudinal wave

3.5.2 Effect of Frequency

During the coal mine test, the transmitted signal frequency was varied between 300 kHz and 20 kHz in order to determine whether the higher or lower frequencies gave more reliable reflected signal data. The correlation between the experimentally deduced reflective layers (Table 3-7) and the data was a measure of this reliability of the data. For a given photograph, this correlation was expressed as a ratio of the number of data points coincident with a layer to the total number of layers. For positions 1 and 4 there were a sufficient number of layers and data points to conduct this analysis of frequency effect. According to Table 3-7, position 1 had seven reflecting layers and position 4 had eight. The correlation ratios for these two positions are given in Tables 3-10 and 3-11, and the average correlation ratio

Table 3-10 - Data Correlation With Signal Frequency

| Position No. 1 | | | | | | |
|--------------------|-------------|------|------|----|------|-------------------|
| | Freq. (kHz) | | | | | Correlation Ratio |
| | 300 | 200 | 150 | 50 | 20 | |
| Photo Numbers | | 2 | | | | 0.14 |
| | | | 3 | | | 0.14 |
| | | | 6 | | | 0.29 |
| | | | 7 | | | 0.14 |
| | | 8 | | | | 0.29 |
| | | 9 | | | | 0.43 |
| | | | 10 | | | 0.57 |
| | | | | 11 | | 0.57 |
| | | 12 | | | | 0.43 |
| | | | 13 | | | 0.43 |
| | | 14 | | | | 0.29 |
| | | 15 | | | | 0.71 |
| | | | 16 | | | 0.57 |
| | | 17 | | | | 0.57 |
| | | 18 | | | | 0.57 |
| | | 22 | | | | 0.57 |
| | | 23 | | | | 0.57 |
| | | 24 | | | | 0.43 |
| | | 69 | | | | 0.43 |
| | | | 70 | | | 0.57 |
| | 71 | | | | 0.57 | |
| | | 72 | | | 0.43 | |
| | | | | 73 | 0.14 | |
| | 74 | | | | 0.57 | |
| | 75 | | | | 0.57 | |
| | | | | 76 | 0.14 | |
| | 77 | | | | 0.57 | |
| | 78 | | | | 0.43 | |
| | 79 | | | | 0.86 | |
| | 80 | | | | 0.43 | |
| Ave. Correl. Ratio | 0.52 | 0.39 | 0.36 | | 0.14 | |

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Table 3-11 - Data Correlation With Signal Frequency

| Position No. 4 | | | | | | |
|--------------------|-------------|------|------|------|------|-------------------|
| | Freq. (kHz) | | | | | Correlation Ratio |
| | 300 | 200 | 150 | 50 | 20 | |
| Photo Numbers | 44 | | | | | 0.50 |
| | | 45 | | | | 0.38 |
| | | | | 47 | | 0.13 |
| | | | | | 48 | 0.13 |
| | | | | 50 | | 0.13 |
| | 51 | | | | | 0.38 |
| | | | | | 53 | 0.25 |
| | | | | | 54 | 0.25 |
| | 55 | | | | | 0.63 |
| | | | 56 | | | 0.63 |
| | | | 57 | | | 0.50 |
| | 58 | | | | | 0.75 |
| | 60 | | | | | 0.63 |
| | | | 61 | | | 0.25 |
| | | | | 62 | | 0.25 |
| | | | | 63 | 0.13 | |
| | | | | 64 | 0.13 | |
| | | | 65 | | 0.25 | |
| | | 66 | | | 0.25 | |
| 68 | | | | | 0.38 | |
| Ave. Correl. Ratio | 0.55 | 0.38 | 0.41 | 0.19 | 0.18 | |

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for each frequency is plotted in Figure 3-13. The general trend exhibited by this figure is that the data become more reliable as the frequency is increased. One reason is that at low frequencies, the wavelength is large compared to the distance between layers, so that adjacent layers are impossible to resolve. For this reason it appeared desirable to evaluate the accuracy of the data at low frequencies versus that of data at high frequencies, rather than the correlation ratio. For comparison, five cases from positions 1 and 4 were selected, and in each case all parameters were held constant except the frequency. Two measurements were made per case: one at 300 kHz and the other at either 20 kHz or 50 kHz. For each case and frequency, the accuracy was defined as the ratio of the data points coincident with a layer to the total number of data points measured. The results shown in Table 3-12 indicate an average data accuracy of 0.86 for 300 kHz signals and 0.67 for 20 kHz signals.

3.5.3 Effects of Coal Surface

The effect of the coal surface on data correlation was determined by dual measurements (one for smooth surface and one for rough surface) for each of five cases. For this purpose, "rough" means no high peaks on the surface, and "smooth" means a surface that has been belt-sanded. The correlation was again defined as the ratio of data points coincident with a layer to the total number of experimentally deduced layers. The results given in Table 3-13 show no significant difference between the measurements.

3.5.4 Effect of Coupling Medium

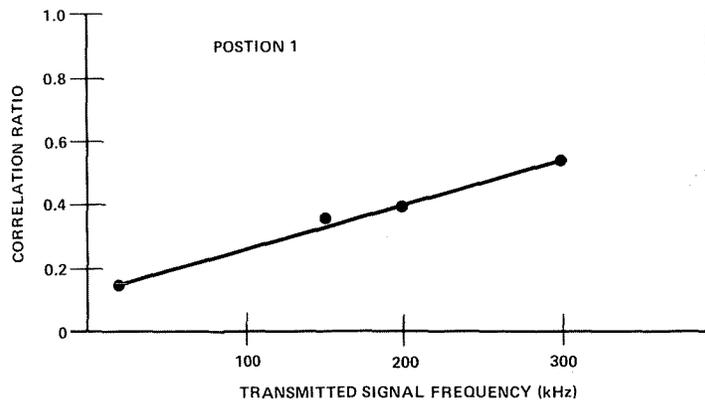
During the coal mine measurements of position 4, water coupling of the transducers to the coal surface was compared to grease coupling, using four cases of dual measurements where all parameters except couplings were fixed. The results given in Table 3-14 for these cases indicate an average correlation ratio of 0.50 for water coupling and 0.35 for grease coupling. Thus water is judged to be the better couplant.

Table 3-12 - Data Accuracy With Transmitted Signal Frequency

| Case | Photo No. | Frequency (kHz) | Data Accuracy |
|------|-----------|-----------------|---------------|
| 1 | 75 | 300 | 1.0 |
| | 76 | 20 | 0.5 |
| 2 | 44 | 300 | 0.8 |
| | 47 | 50 | 0.5 |
| 3 | 44 | 300 | 0.8 |
| | 48 | 20 | 1.0 |
| 4 | 58 | 300 | 0.86 |
| | 62 | 50 | 1.0 |
| 5 | 58 | 300 | 0.86 |
| | 63 | 20 | 0.33 |

Ave. = 0.86 (300 kHz)
Ave. = 0.67 (20 kHz nominal)

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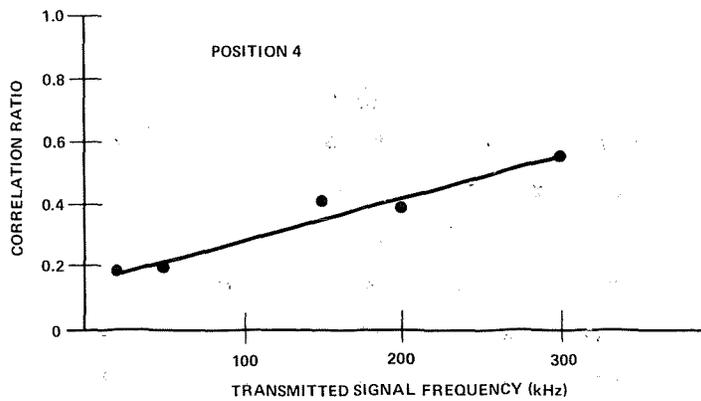


Figure 3-13 - Data Correlation With Transmitted Signal Frequency

Table 3-13 - Effect of Surface Condition on Correlation Ratio

| Case | Photo No | Surface | Correlation Ratio |
|---|----------|---------|-------------------|
| 1 | 22 | rough | 0.57 |
| | 23 | smooth | 0.57 |
| 2 | 44 | rough | 0.50 |
| | 58 | smooth | 0.75 |
| 3 | 45 | rough | 0.38 |
| | 61 | smooth | 0.25 |
| 4 | 47 | rough | 0.13 |
| | 62 | smooth | 0.25 |
| 5 | 48 | rough | 0.13 |
| | 63 | smooth | 0.13 |
| 6 | 50 | rough | 0.13 |
| | 65 | smooth | 0.25 |
| Rough Ave. = 0.31 Smooth Ave. = 0.37 | | | |

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Table 3-14 - Effect of Coupling on Correlation Ratio

| Case | Photo No. | Coupling | Correlation Ratio |
|---|-----------|----------|-------------------|
| 1 | 55 | water | 0.63 |
| | 58 | grease | 0.75 |
| 2 | 56 | water | 0.63 |
| | 61 | grease | 0.25 |
| 3 | 54 | water | 0.25 |
| | 64 | grease | 0.13 |
| 4 | 57 | water | 0.50 |
| | 66 | grease | 0.25 |
| Ave. = 0.50 water Ave. = 0.35 grease | | | |

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3.5.5 Effect of Filtering

As mentioned earlier, electronic filtering of the received signal was primarily high-pass HP (48 dB/octave) or minimum band-pass BP (24 dB/octave). HP filtering reduced the 60 Hz fluctuation of the signal without altering the high frequency components, whereas BP filtering reduced the amplitude of all frequency components with respect to the fundamental. When the correlation ratios of six cases of dual measurements (identical except for the filtering) at position 4 were compared, it was found that the correlation is independent of filtering. (See Table 3-15).

3.5.6 Effect of Transducer Placement

During the tests, it was recognized that the placement of the transducer within a position affected the received signal. This effect was verified at position 1 where seven measurements were taken to show the effect of 1/8" variations in the locations of transducers within position 1. Table 3-16 shows the variation in the correlation ratios with transducer placement. The deviation from the mean in these values ranged from +56% to -22%. Later visual examination of the coal samples revealed a significant number of vertical calcite layers which could be responsible for the variations observed.

3.5.7 Effect of Time on Reflected Signals

During this study, two important questions have arisen:

- Do cracks inherent in coal become progressively worse after mining?
- Do the cracks change within minutes after mining?

The second question could not be resolved due to scheduling problems between the mining operation and test equipment setup. Therefore, we set out to answer the first question using data from position 1 where measurements were taken on each of four days from April 25 through April 28.

The peak-to-peak signal amplitude data from five reflecting layers in position 1 are given in Table 3-17 and plotted in Figures 3-14 through 3-18. As can be seen, these figures do not show any consistent

Table 3-15 - Effect of Filtering on Correlation Ratio

| Case | Photo No. | Filter | Correlation Ratio |
|----------------|-----------|--------|-------------------|
| 1 | 47 | HP | 0.13 |
| | 50 | BP | 0.13 |
| 2 | 48 | HP | 0.13 |
| | 49 | BP | 0.13 |
| 3 | 58 | HP | 0.75 |
| | 60 | BP | 0.63 |
| 4 | 63 | HP | 0.13 |
| | 64 | BP | 0.13 |
| 5 | 61 | HP | 0.25 |
| | 66 | BP | 0.25 |
| 6 | 56 | HP | 0.63 |
| | 57 | BP | 0.50 |
| Ave. = 0.34 HP | | | |
| Ave. = 0.30 BP | | | |

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Table 3-16 - Effect of Transducer Placement on Correlation Ratio

| Photo No. | Placement | Correlation Ratio |
|---|-----------|-------------------|
| 69 | 1 | 0.43 |
| 71 | 2 | 0.57 |
| 74 | 3 | 0.57 |
| 77 | 4 | 0.57 |
| 78 | 5 | 0.43 |
| 79 | 6 | 0.86 |
| 80 | 7 | 0.43 |
| Ave. = 0.55 | | |
| Deviation = $\left\{ \begin{array}{l} + 0.31 \dots + 56\% \\ - 0.12 \dots - 22\% \end{array} \right.$ | | |

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Table 3-17 - Signal Amplitude Change With Time

Position No. 1

| 0.7" Boundary | | |
|---------------|-----------|----------------|
| Date | Photo No. | P-P Ampl. (mV) |
| 4/25 | 3 | 0.2 |
| 4/26 | 6 | - |
| ↓ | 8 | 0.8 |
| ↓ | 9 | 0.25 |
| ↓ | 11 | 0.32 |
| ↓ | 12 | 1.5 |
| ↓ | 13 | 1.3 |
| ↓ | 14 | 1.3 |
| ↓ | 15 | 0.3 |
| ↓ | 16 | 0.3 |
| ↓ | 17 | 0.4 |
| ↓ | 18 | 0.4 |
| 4/27 | 22 | 0.2 |
| ↓ | 23 | 0.3 |
| ↓ | 24 | 0.75 |
| 4/28 | 69 | 0.8 |
| ↓ | 70 | 1.2 |
| ↓ | 71 | 1.0 |
| ↓ | 72 | 1.5 |
| ↓ | 77 | 0.4 |
| ↓ | 79 | 0.4 |

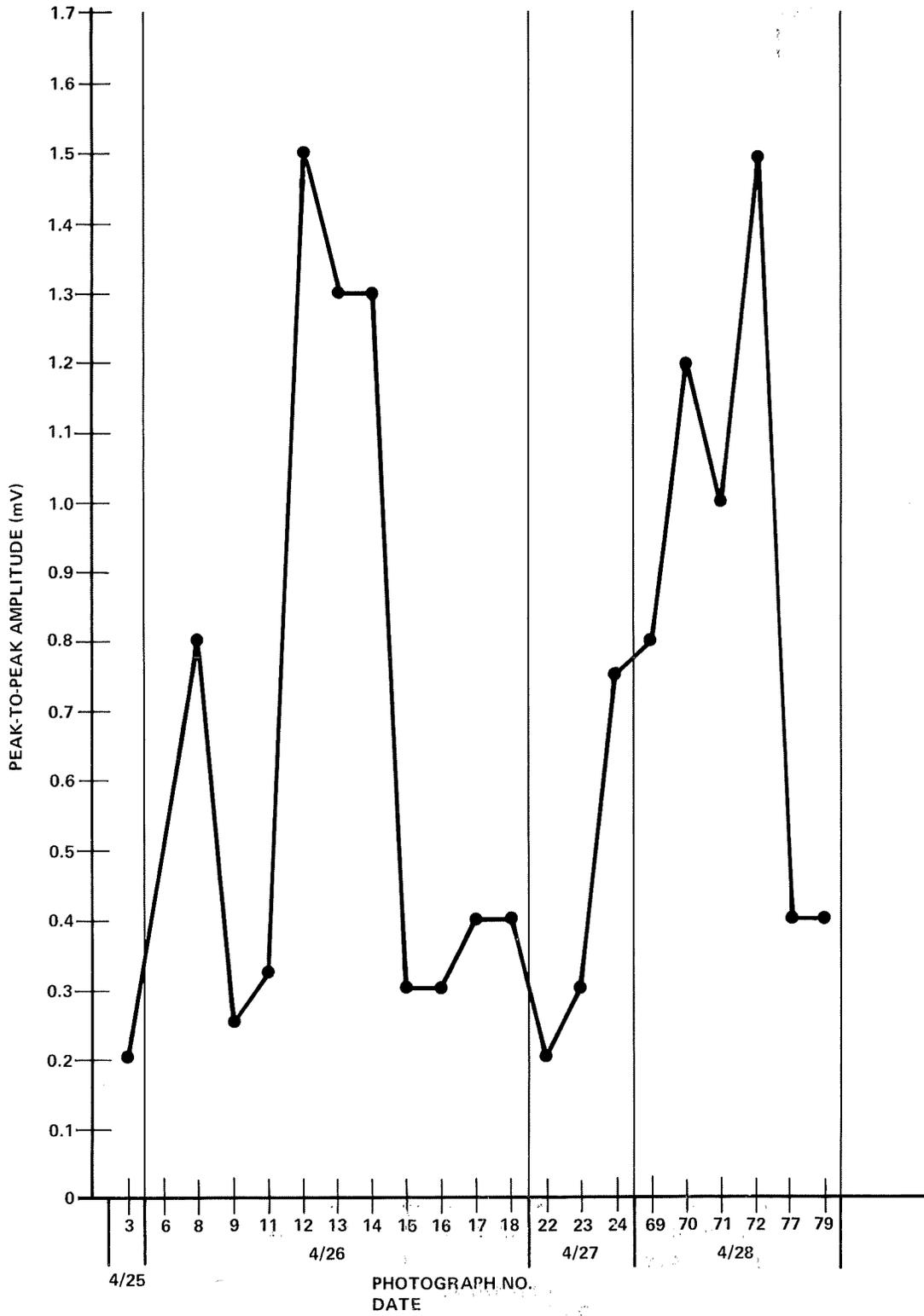
| 1.5" Boundary | | |
|---------------|-----------|----------------|
| Date | Photo No. | P-P Ampl. (mV) |
| 4/26 | 7 | 1.5 |
| ↓ | 9 | 0.3 |
| ↓ | 12 | 0.6 |
| ↓ | 13 | 0.8 |
| ↓ | 14 | 0.7 |
| ↓ | 21 | 0.1 |
| 4/28 | 70 | - |
| ↓ | 72 | 0.2 |
| ↓ | 73 | - |
| ↓ | 74 | 0.7 |
| ↓ | 75 | 0.2 |
| ↓ | 76 | - |
| ↓ | 77 | 0.6 |
| ↓ | 78 | 0.4 |
| ↓ | 79 | 0.5 |
| ↓ | 80 | 0.3 |

| 2.6" Boundary | | |
|---------------|-----------|----------------|
| Date | Photo No. | P-P Ampl. (mV) |
| 4/26 | 6 | 0.5 |
| ↓ | 8 | 0.5 |
| ↓ | 10 | 0.2 |
| ↓ | 11 | 0.2 |
| ↓ | 15 | 1.5 |
| ↓ | 17 | 2 |
| ↓ | 18 | 2 |
| 4/27 | 22 | 0.3 |
| ↓ | 23 | 0.3 |
| ↓ | 24 | 0.6 |
| 4/28 | 69 | 0.7 |
| ↓ | 70 | 1 |
| ↓ | 72 | 0.5 |
| ↓ | 77 | 0.7 |
| ↓ | 79 | 0.6 |
| ↓ | 80 | 0.4 |

| 1.9" Boundary | | |
|---------------|-----------|----------------|
| Date | Photo No. | P-P Ampl. (mV) |
| 4/25 | 2 | 0.3 |
| 4/26 | 10 | 0.6 |
| ↓ | 11 | 0.7 |
| ↓ | 15 | 3.8 |
| ↓ | 16 | 3 |
| ↓ | 17 | 6 |
| ↓ | 18 | 6 |
| 4/27 | 22 | 1.30 |
| ↓ | 23 | 1.25 |
| ↓ | 24 | 1.0 |
| 4/28 | 69 | 0.9 |
| ↓ | 71 | 1.3 |
| ↓ | 74 | 3.5 |
| ↓ | 75 | 1.2 |
| ↓ | 79 | 0.5 |

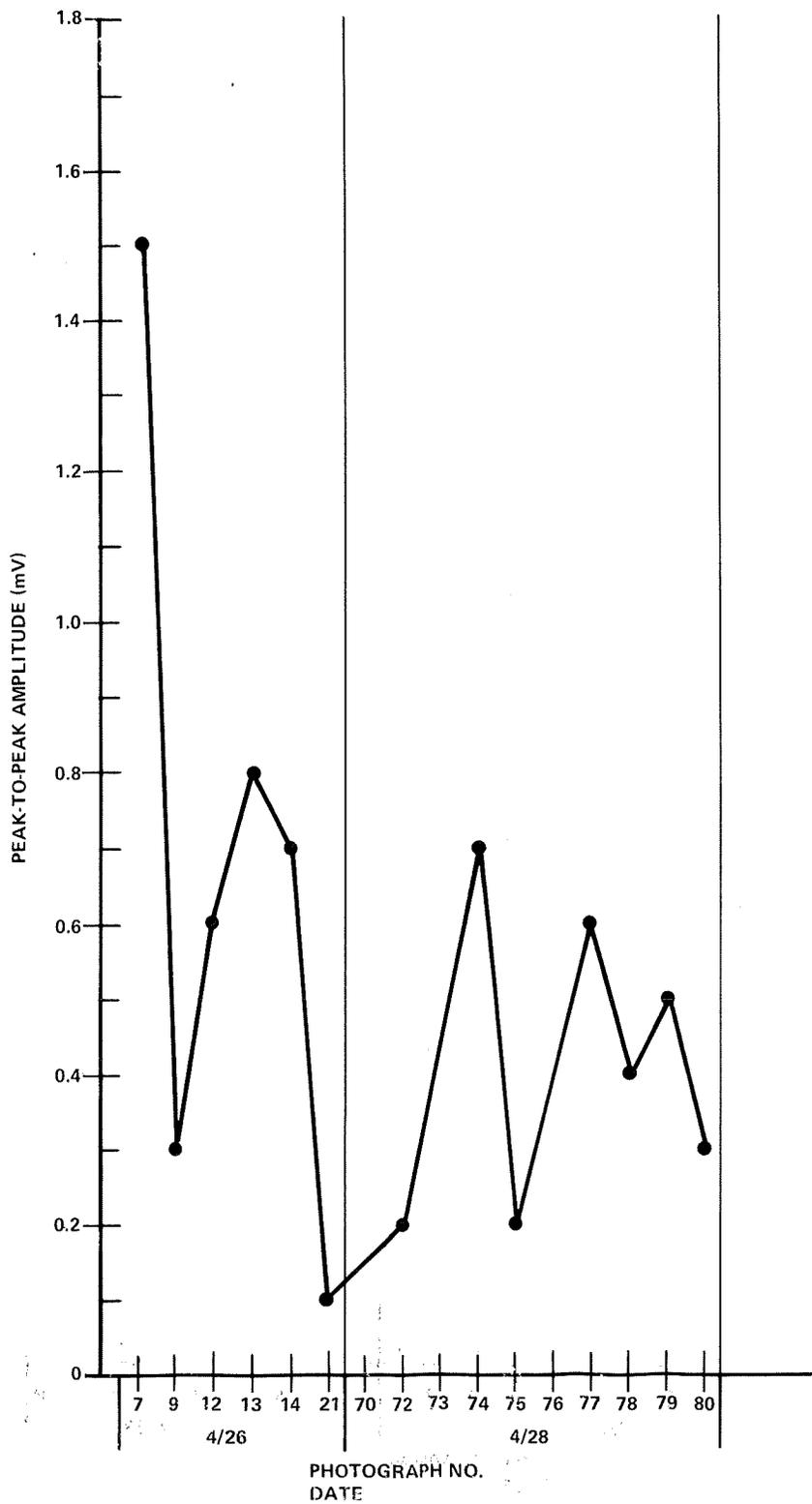
| 3.9" Boundary | | |
|---------------|-----------|----------------|
| Date | Photo No. | P-P Ampl. (mV) |
| 4/26 | 10 | 0.16 |
| ↓ | 15 | 0.5 |
| ↓ | 16 | 0.8 |
| 4/28 | 70 | 0.8 |
| ↓ | 80 | 0.2 |

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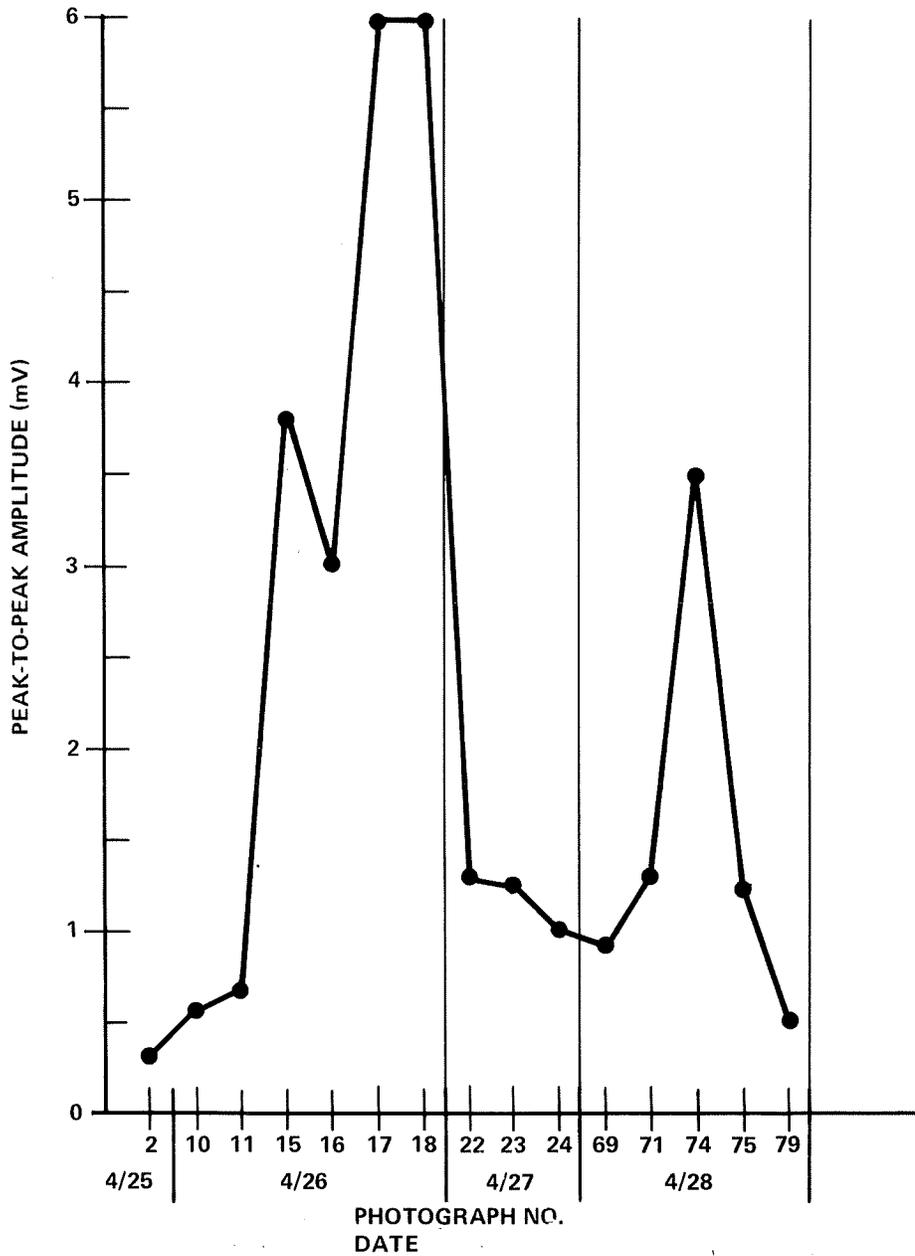
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Figure 3-14 - Signal Amplitude Change With Time for 0.7-Inch Reflecting Layer of Position 1



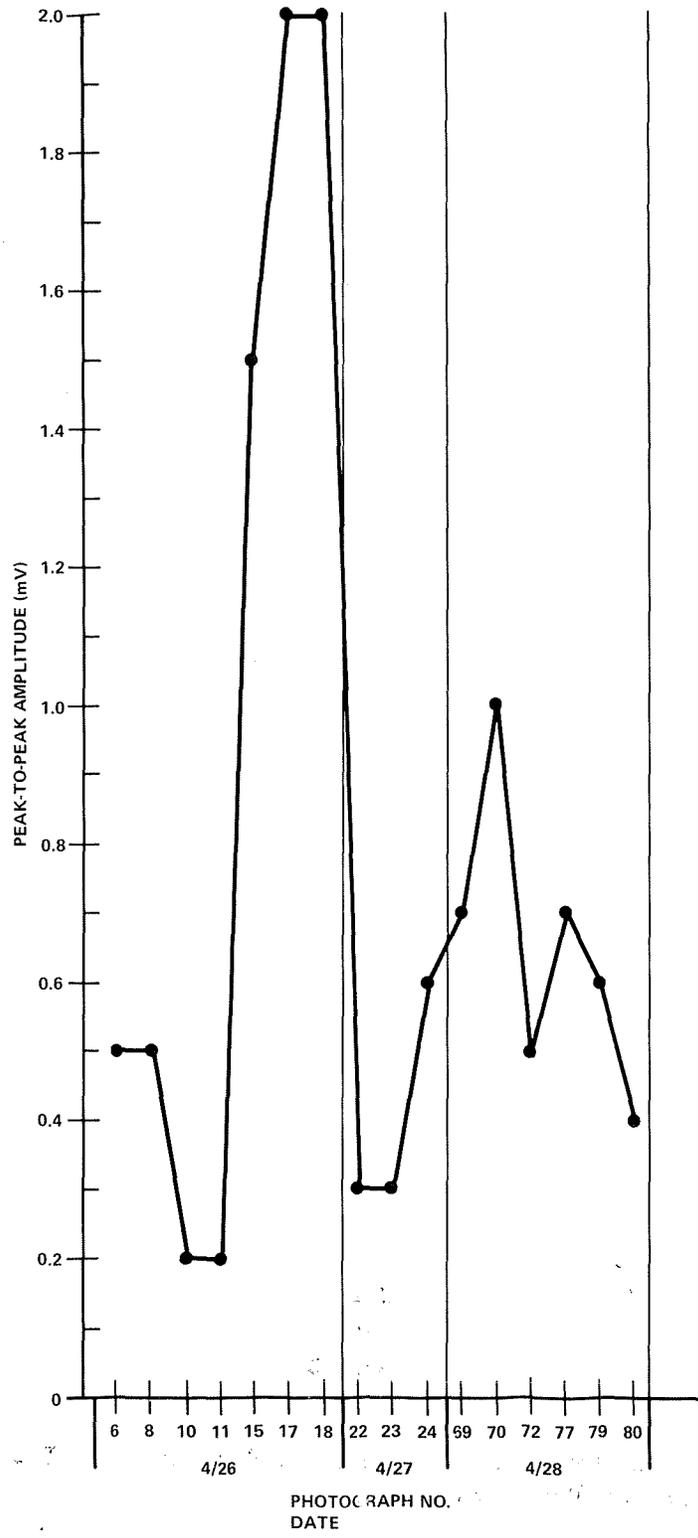
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Figure 3-15 - Signal Amplitude Change With Time for 1.5-Inch Reflecting Layer of Position 1



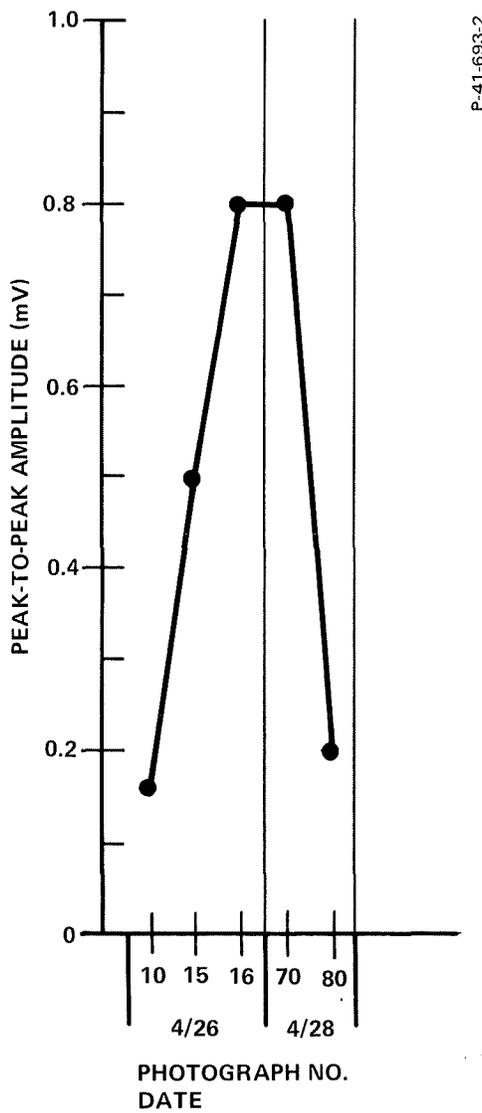
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Figure 3-16 - Signal Amplitude Change With Time for 1.9-inch Reflecting Layer of Position 1



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Figure 3-17 - Signal Amplitude Change With Time for 2.6-Inch Reflecting Layer of Position 1



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Figure 3-18 - Signal Amplitude Change With Time for 3.9-Inch Reflecting Layer of Position 1

trend to reduced signal amplitude with time. There are two possible conclusions: (1) the reflecting layers had no cracks, or (2) any cracks associated with the five layers did not change over a 4-day period.

3.6 FIELD TEST CONCLUSIONS

It was impossible to establish the extent to which cracks exist in freshly mined coal (within minutes of mining). Two major reasons for this were that: (1) it was not possible to set up test equipment fast enough to measure and assess the coal surface within a few minutes of the mining and (2) it was impossible to establish whether the intact roof coal had any cracks. Removal of the samples introduced the possibility that cracks were imposed upon the sample. The fact that the reflected signal amplitudes did not show any decreasing trend over a one- to three-day period after mining indicates that crack formation, if it does occur, is not a rapidly varying function.

Test results showed that such layers as pyrite and gossan, abundantly present in Old Ben coal, reflect back a part of the transmitted acoustic wave. These signals were not readily distinguishable from the signal reflected by the coal/shale interface. Furthermore, in some cases, the transmitted signal reaching the interface appeared to be sufficiently attenuated by the above layers, such that the reflected signal was lost in the noise.

The effect of the vertical calcite layers observed in Old Ben coal could well be to isolate the reflected signal from the separate receive transducer. It might also be presumed that shear waves could be reflected back to the receiver, confusing the return signal signature. The transceiver mode of operation would have been more suitable for this case.

3.7 SUMMARY

The analysis of the Old Ben Coal Mine field test data led to the following conclusions:

- (1) Although the coal/shale interface was detected in three of the five test site locations at Old Ben using the acoustic

pulse-echo technique, without *a priori* knowledge, that signal could not be distinguished from other reflections.

- (2) Impurity layers, such as pyrite, gossan, and calcite along with cracks consistently reflected signals which competed with and confused the coal/shale reflected signal.
- (3) In some cases, the attenuation of the transmitted signal by impurity layers and cracks prohibited any detectable return from the coal/shale interface.
- (4) Vertical calcite layers in the coal adversely affected the received signal.
- (5) Transmitted frequencies of 300 kHz yielded a higher correlation ratio* than lower frequencies.
- (6) Coupling of the transducer to a moderately rough coal surface gave the same signal return signature as coupling to a smooth surface.
- (7) Water coupling between the transducer and coal gave a higher correlation ratio than grease coupling.
- (8) Minimum band-pass (BP) filtering of the received signal, as compared to high-pass (HP) filtering, did not improve the signal-to-background noise ratio.
- (9) The amplitudes of the reflected signals did not exhibit any increasing or decreasing trend over a one- to three-day time span. This indicates that crack formation (if it does indeed occur) is not a rapidly varying function.

Based on the results from this field test, we do not recommend further development of the system at this time. The structure of the coal at the Old Ben test site was such that the use of acoustic reflection to measure coal thickness was not practical.

Since other mines may not have the degree of impurity layers encountered at the Old Ben mine, we feel that the acoustic-reflection method may have limited application. Before further development of hardware based on acoustic reflection, the percentage of coal mines having coal amenable to measurement by acoustic reflection should be

determined. This determination could be made by obtaining core samples of roof coal at various mines and inspecting them optically for impurity layering and cracks, and/or by performing a simple acoustic-reflection measurement *in situ*. The latter approach is recommended because of the problem of extracting coal without damage to the sample itself. This acoustic reflection test for a given mine could be conducted within two days.

SECTION 4

NUCLEONIC BACKSCATTERING COAL SEAM INTERFACE SENSOR

Although the bulk of the work during this contract period was related to the acoustic coal seam interface sensor, an effort was also made to find out as much as possible about the nucleonic (gamma-ray) backscattering sensor being developed by the British Coal Board Establishment.

As reported in the Preliminary Design Review Document, Bendix Report No. 6040, a gamma-ray backscattering sensor has been under development by the British Coal Board Mining Research and Development Establishment since the early 1960's. The published papers relating to this sensor include:

- (1) B. P. Pidgeon and V. M. Thomas, "Remote Control of Face Machinery, 1-Coal-Winning Machines," Proceedings of the Symposium on Remote Control of Electrical and Mechanical Equipment at the Coalface, Harrogate, England, November 1964.
- (2) S. F. Powell and J. A. Homer, "Automatic Steering of Coal-cutting Machines," G.E.C. Journal, Vol. 34, No. 2, 1967.
- (3) D. Hartley, "Automatic Steering of the Shearer Loader at Wolstanton Colliery," The Mining Engineer, January 1971.

The sensor, as described in these papers, was used in various experimental applications with varying success. In the later paper, the results are optimistic and indicate that this method of measuring coal thickness up to 7 (or perhaps 10 inches) is feasible, at least in mines with a coal seam greater than four feet in thickness.

Several efforts were made to talk with people at the British Coal Board directly to learn more about the sensor, including its resolution and range capabilities and any problem areas that exist. One such telephone contact was made with Mr. A. E. Bennett, Deputy Director of the Mining Research and Development Establishment. Before any information

could be obtained, however, telephone contact was lost. When further efforts were made to contact the Coal Board, we were informed that they would be willing to discuss details of the sensor only upon payment of a fee. This fee was later established to be 20,000 pounds sterling. We rejected these conditions.

In addition to trying to make contact with the British Coal Board, a letter was sent to the Salford Electrical Instruments Limited, developers and manufacturers of the Nucleonic Coal Sensing Probe, requesting information on its specifications and price quotations. The answer to this letter indicated the sensor could be used to measure up to 10 inches of coal, but no other specifications were given. A price quotation of 5,050 pounds was given; however, they suggested we make contact with the Mining Research and Development Establishment and visit with them before we place an order for the equipment.

In summary, efforts to obtain detailed information about the nucleonic sensor were met with frustrations. It appears that the only way a private industrial firm such as Bendix can obtain additional information is by paying a rather large fee to the Coal Board. Therefore, Bendix recommends that further requests for information from the British Coal Board be negotiated directly by the U.S. Bureau of Mines.

With respect to the operation of a gamma-ray sensor in a mine such as the Old Ben mine where the acoustic field test was made, we believe that its performance may degrade substantially due to the number of pyrite and calcite impurity layers in that coal. The operation of the gamma-ray sensor depends on the scattering and attenuation coefficients of the coal. These coefficients are in turn dependent on the z (atomic number of the elements). The scattering coefficient is linear with z but the absorption coefficient increases as z^3 . The result for high z (compared to coal) layers is that the scattering is increased to some degree and the absorption is increased to a larger degree. If the population of these layers is not constant (as they were not at Old Ben) the calibration of a gamma-ray sensor would be difficult and the resultant resolution unpredictable.

SECTION 5
CONCLUSIONS

The study reported here has shown that the acoustic technique is not a general solution to the problem of measuring coal thickness. The primary reason for this conclusion is the fact that some head (and floor) coal (e.g., that in Old Ben mine) contains several impurity (or foreign) layers or alternating layers of different carbonification. These layers, along with any horizontal cracks that might be present, scatter and reflect the acoustic radiation and make it extremely difficult to identify the desired reflection from the seam interface.

Although the acoustic technique - using present state-of-the-art methods - is not a general solution, it should still be possible to use it for certain particular cases. For example, laboratory experiments were performed with coal mined in Kentucky which had few impurity layers, but did have layers with varying degrees of carbonification. Acoustic energy was easily transmitted through this coal and reflections from simulated coal-overburden interfaces were detected.

The coal interface detection problem is an extremely difficult one. As noted earlier, the presence of foreign impurity layers in the coal certainly limits the application of acoustic methods. These layers, however, will also affect other techniques. The resolution of the gamma-ray backscattering method would be degraded because of the differences in the scattering and absorption properties of the layers compared to the host coal. The presence of certain hard layers (e.g., iron pyrite) of sufficient thickness will also hinder mechanical drilling techniques as it will be difficult for the drill to penetrate these layers. Because of these factors, it appears that any one coal-seam interface detection method will prove lacking under certain conditions, and the development of a universal interface detection scheme may be impossible.

Comparing the capabilities of the acoustic and gamma-ray back-scattering techniques, the results of the study indicate that the gamma-ray backscattering approach does have more potential. Although its resolution will be degraded by certain factors already discussed, these same factors may make the use of acoustic methods impractical. Further, the presence of horizontal cracks in the roof (or floor) coal should not limit the application of the gamma-ray method as drastically as that of the acoustic method.

SECTION 6

RECOMMENDATIONS

The serious difficulties in the general application of acoustic methods to seam interface detection which were exposed by the present study lead us to recommend that the nucleonic (gamma-ray) backscattering technique be considered the primary candidate for seam thickness measurement. Although the resolution of this method is influenced by impurities in the coal and its range is limited, it appears that this method is practical under some conditions where acoustics is not. It is unfortunate that we were unable to obtain the necessary detailed information on this method to completely evaluate it due to difficulties in dealing with the United Kingdom National Coal Board. This information is supposedly available from the Coal Board, however, subsequent to the payment of a fee. Therefore, we recommend that the U.S. Bureau of Mines, or an appointed contractor, actively pursue obtaining the required information to evaluate the potential of the gamma-ray backscattering method.

If the gamma-ray method should also turn out after further investigation to be unsuitable or limited for the seam interface problem, then other techniques will need to be considered or reconsidered. For example, an acoustic method in a somewhat different form might be possible. Under conditions similar to that encountered in the Old Ben Coal Mine, where the seam interface is continuous, but the foreign impurity layers are not, acoustic reflections might be averaged as the mining machine moves along. The reflections from randomly distributed foreign layers will tend to cancel and average out to a small value. A more detailed description of an averaging technique is given in Appendix C.

Another method which should be considered is the measurement of torque load on a constant-speed drill placed on a stage which moves on the mining machine such that the drill is fixed relative to the coal

during measurement. One version of such a method is described in Appendix D. Actually, mechanical drilling techniques should find application in U.S. coal mines where the mining machine is stationary for short periods of time (less than a minute) during the normal operating cycle.

In summary, we recommend that the gamma-ray backscattering technique be investigated further to determine if it meets the U.S. Bureau of Mines' requirements for detecting coal seam interfaces. Further, because the structure of coal varies widely, as do mining procedures, and the development of a single interface detection system to serve all needs may not be possible, we recommend that each individual mine be treated as a separate case in determining the type of interface sensor best suited for it.

APPENDIX A
ANALYSIS OF ACOUSTIC-REFLECTION COAL SEAM
INTERFACE SENSOR

This analysis was previously presented in the Preliminary Design Review document, "Feasibility of Remote Control and Development of Remote Control Devices and Sensors, Vol. 2, Continuous Mining Machine Seam Interface Sensors," Bendix Report No. 6040, November 1971. It is repeated here for completeness of this report.

The acoustic pulse reflection method is well established as a non-destructive means of testing materials both for thickness and internal flaws.¹ The basis of the method is to transmit a burst of acoustic energy into the test object; this acoustic signal is then reflected off the flaw or far surface of the test object back toward the receiving transducer. The transit time t required by the signal to reach the receiver can be used to determine the distance z to the flaw or back surface:

$$z = \frac{vt}{2}$$

provided that the velocity of sound v in the object is known. Since in most testing applications the velocity is a fixed quantity, the resolution of depth is directly related to the accuracy of reading the arrival time. Any inaccuracy in reading the arrival time is usually a fixed value independent of the total time; hence the error is a fixed quantity and is not a fixed percentage of the total depth in the object.

In the typical application of the reflection method for determining thickness of metals, the acoustic transducer unit is used both for generating the test signal as well as for receiving the returned signal; however, separate transmit and receive units may also be used. The test

signal is usually generated by applying to the transducer either a short pulse-modulated CW carrier or a dc voltage pulse that excites the transducer to "ring" at its resonant frequency for several oscillations. Normally, a collimated acoustic signal is created at the high frequencies used in metal testing applications. This signal is then reflected off the interface under test and returned. The amount of energy reflected from the interface is a function of the difference between the acoustic impedances of the two materials. For instance, an air backing will reflect almost 100 percent of the energy back into the material, while a backing of almost the same acoustic impedance will allow most of the energy to be transmitted across the interface. The acoustic signal sent into the material under test can lose energy not only by reflection but also by internal absorption in the material. However, the low absorption in metals usually makes this a minor problem. The returned signal is usually detected by the same transducer unit that generated the signal, after a short "dead time" for the transducer to begin receive operation. Consequently, there is a minimum resolvable distance in the pulse reflection method which is a function of the pulse width and electronic switching time.

In analyzing the pulse reflection method for possible use in measuring coal thickness, the above mentioned characteristics must be studied in relation to coal. The method has been successfully used to measure coal thickness² up to 57 inches. But the conditions for measuring 1/2 to 12-inch layers of coal left on the roof and floor after a seam has been mined are different and must be properly analyzed. For this analysis, information on the mechanical and acoustical properties of coal (such as velocity of sound, density, and the acoustic absorption) must be known; in addition, information on the typical strata located above and below the coal seam must be known.

Information on the density and velocity of sound for coal has been gathered from several sources.^{3,4,5,6} Figure A-1, taken from Van Krevelen and Chermin shows the relationship of the density in vitra type coal

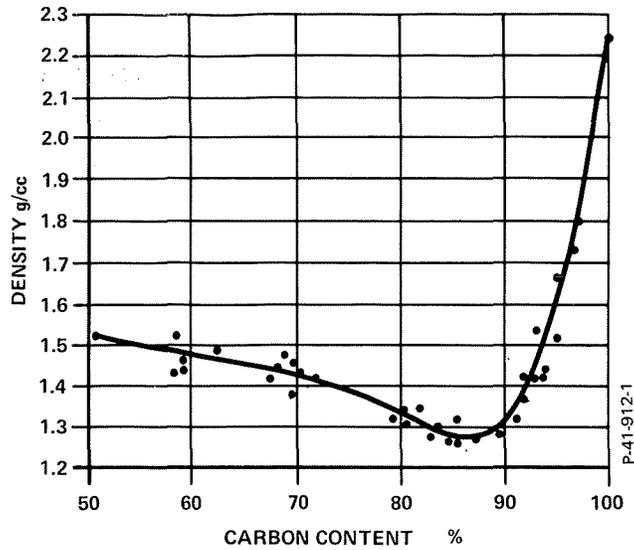


Figure A-1 - True Density of Coal

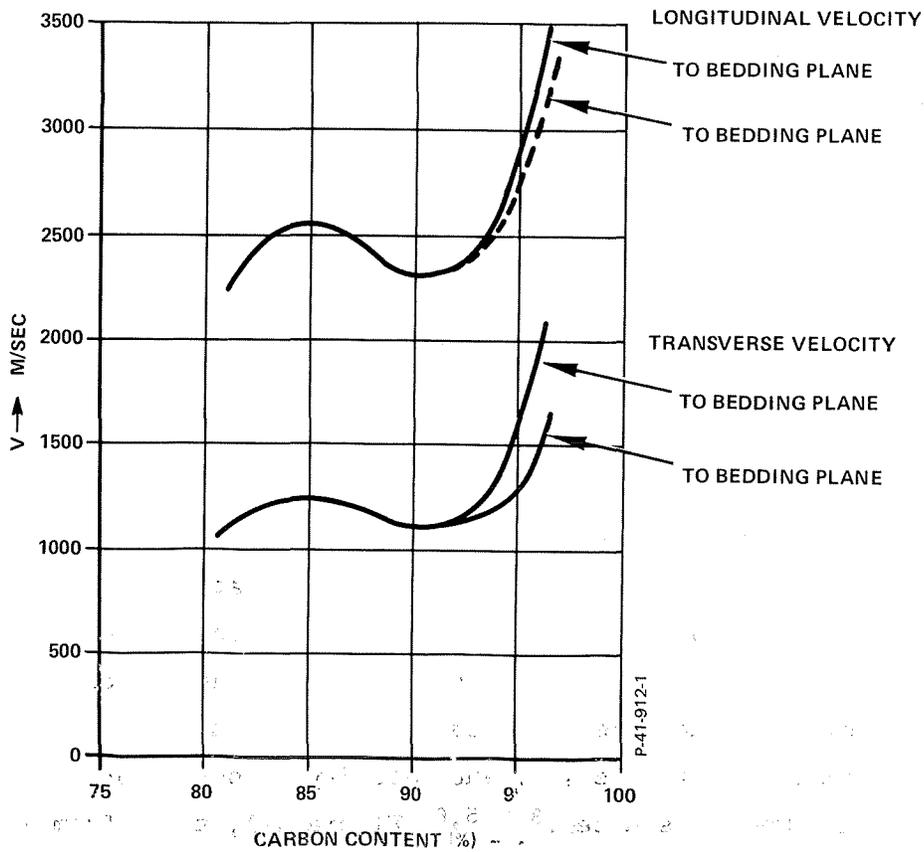


Figure A-2 - Velocity of Air Flow in Vitrains at 20°C

as a function of carbon content. Well logging information in the paper by Bond, Alger, and Schmidt give representative values for density and velocity in a No. 6 coal bed. It has also been shown that the velocity of sound varies with the rank of coal.⁵ Figure A-2, taken from Schuyer, Dijkstra, and Van Krevelen shows this variation in the longitudinal and transverse velocities as a function of carbon content. In addition, the longitudinal velocity in a sample of coal, measured experimentally in the laboratory, agrees with the selected average value.

Since a typical overburden encountered in a coal mine is shale, and since the floor is often a clay base, these two materials have been selected as the strata located above and below the coal seam for analysis purposes. For this analysis, the use of other strata material would lead to improved results using the acoustic methods of measuring coal thickness; therefore, the use of shale and clay can be considered the worse case. Values for the velocity of sound and density in shale and clay have been gathered from various sources.^{4,7,8,9,10,11,12}

Table A-1 gives the values for the velocity of sound and density that were selected for use in the analysis work as well as the acoustic impedance ($W = \rho v$); these values are felt to be representative of typical bituminous coal mined in the United States.

A good value for the coefficient of attenuation of acoustic waves in coal was not found in the literature. Koltonski and Malecki¹³ in Poland did report attenuation values for a pit coal; however, this pit coal is likely to be a brown coal from the lignite series and hence has much larger attenuation values than those expected for bituminous coal mined in the U.S. Some typical values for the absorption or attenuation coefficients for roof rock in coal mines were found.^{2,8,14} From the information that could be gathered, it seemed reasonable to assume that the absorption coefficient would be halfway between the values for the pit coal and the values for the typical roof rock. Therefore, a value for the absorption constant of coal was taken to be

$$k = 91 \times 10^{-8} \text{ sec/cm } (2.3 \times 10^{-6} \text{ sec/in})$$

Table A-1 -- Assumed Physical Constants for Coal Mine Strata

| Material | ρ Density | v Velocity | W Acoustic Impedance |
|----------|-------------------------|--|------------------------------|
| Coal | 1.4 gm/cm ³ | 2.35 x 10 ⁵ cm/sec (9.24 x 10 ⁴ in/sec) | 3.3 x 10 ⁶ (MKS) |
| Shale | 2.5 gm/cm ³ | 2.65 x 10 ⁵ cm/sec (10.4 x 10 ⁴ in/sec) | 6.6 x 10 ⁶ (MKS) |
| Clay | 2.45 gm/cm ³ | 2 x 10 ⁵ cm/sec (7.88 x 10 ⁴ in/sec) | 4.9 x 10 ⁶ (MKS) |
| Water | 1 gm/cm ³ | 1.5 x 10 ⁵ cm/sec (5.9 x 10 ⁴ in/sec) | 1.5 x 10 ⁶ (MKS) |

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For solids, the absorption is a linear function of the frequency, to a first approximation $\alpha_a = kf$. The amplitude of the acoustic signal in coal as a function of distance (neglecting beam spread) is given by $A = A_0 e^{-\alpha_a x}$. The attenuation of the acoustic signal can also be expressed in decibels by

$$\text{Attenuation} = 8.68 \alpha_a x = 8.68 kfx \text{ (dB)}$$

For example, in coal at $f = 100$ kHz, the attenuation per unit length is

$$\text{Attenuation} = 80 \text{ dB/meter} \approx 2 \text{ dB/in}$$

In analyzing the practicality of using the pulse reflection method to determine the coal thickness, two types of transducer coupling to coal were included: (a) water jet coupling and (b) semi-direct contact.

The water jet coupling offers the advantage of easier coupling to a non-smooth coal surface. In this coupling, the acoustic pulse from the transducer travels through the water and impinges upon the coal. Part of the acoustic energy enters into the coal and part is reflected back into the water. The signal that enters the coal then travels to the coal-shale interface where part of it is reflected back and reenters the water jet. In order to resolve the first half inch of coal, the acoustic pulse must be made short enough so that the leading edge of the pulse that is reflected off the coal-shale interface and reenters the water does not overlap the trailing edge of the pulse reflected off the water-coal interface. This means that the pulse width must be

$$t < \frac{2Z}{v_c} = \frac{2 (1/2 \text{ in.})}{9.24 \times 10^4 \text{ in/sec}}$$

$$t \approx 10 \text{ } \mu\text{sec}$$

At the same time, the path length of the acoustic signal in the water jet must be made long enough so that multiple reflections that take place in the water jet do not overlap any signal returned from the coal-shale interface. If a signal from a 12-inch thick coal layer must be seen, the time necessary for a signal to travel in coal from the water-coal interface to the coal-shale interface and then return to the water-coal interface must be shorter than the time necessary for the reflected signal in water to travel from the coal-water interface back to the transducer and then be reflected back to the water-coal interface. See Figure A-3.

The transit time through the coal is then

$$T_c = \frac{2Z}{v_c} = \frac{2 \times 12}{9.24 \times 10^4} = 260 \text{ } \mu\text{sec}$$

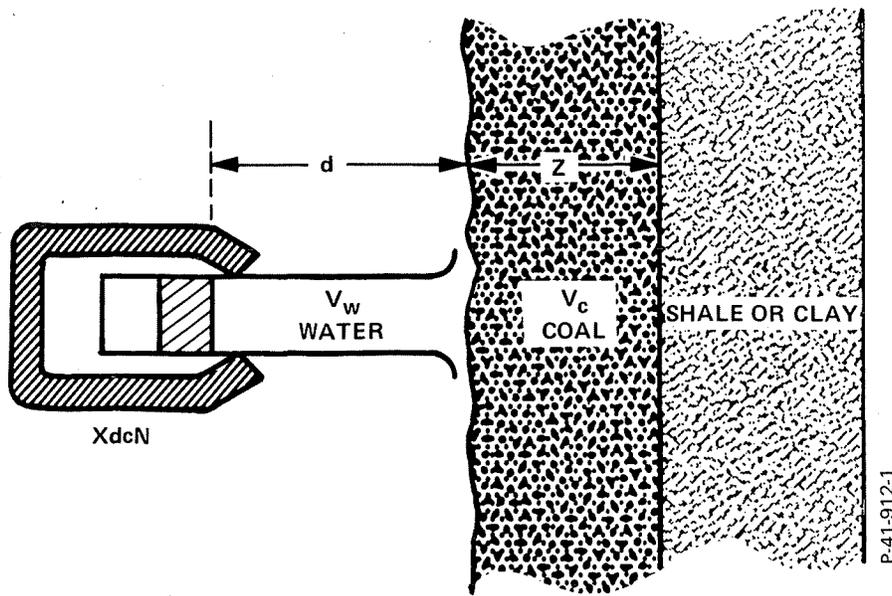


Figure A-3 - Water Jet Coupling to Coal Layer

Since $T_w > T_c$, where T_w is the transit time in water

$$T_w = \frac{2d}{v_w}$$

then

$$d = \frac{T_w v_w}{2} > \frac{T_c v_w}{2} > \frac{260 \text{ sec } 5.9 \times 10^4}{2} > 7.7 \text{ inches}$$

On the practical side, a water column at least 8 inches long is not desirable because, at the frequencies that would be used, the acoustic beam would be rather divergent and not collimated. This means that the generation of internal reflections off the sides of the water column would still interfere with the received true signal; secondly, the extra long water path would double the losses normally seen because of a divergent acoustic beam. It is therefore recommended that a water jet coupling

method not be used when the transducer is operated as a transceiver unit. If a separate transmitter and receiver are used, however, the water jet coupling technique is feasible if the path length is kept short.

The second method of coupling does offer a solution to the multiple echo problem. In this coupling, the water column would be shortened so that the water path would be much less than a quarter wavelength, or even shortened to the extent that the transducer is actually touching the coal, with the water only filling any voids left by the surface irregularities. In effect, the transducer would see the impedance of the coal and not the impedance of the water.

In order to properly analyze the reflection method using a semi-direct coupling contact, attenuation losses to the signal should be studied. In the pulse reflection method there are three ways to lose energy in the reflected pulse: (a) absorption losses, (b) reflection losses at coal-shale or coal-clay interface, and (c) geometric spread in the acoustic beam. To study these losses, the frequency of the signal should be known.

In order to resolve a 1/2-inch thick layer of coal with a direct contacting transducer, the pulse width of the acoustic signal still must be 10 μ sec or less to avoid overlap of the leading and trailing edges (the trailing edge still being generated in the transducer and the leading edge reflected from the coal-shale interface). If a properly damped transducer unit will create an acoustic pulse train that is no more than 5λ long, then this 5λ pulse occurring in 10 μ sec is equal to a 500 kHz acoustic frequency.

The attenuation losses that occur to the test signal of 500 kHz sent into the roof of a coal mine can now be determined. The losses due to geometric spreading of the beam can be neglected at this high frequency because it will be somewhat collimated if a large area transducer is used.

When the test pulse signal is reflected off the coal-shale interface, there is a loss in amplitude. The ratio of the amplitude of the

acoustic wave incident on the interface to the wave reflected is given by

$$R = \frac{W_2 - W_1}{W_2 + W_1}$$

where

W_2 = acoustic impedance of shale or clay

W_1 = acoustic impedance of coal

For a coal-shale interface, $W_2 = 6.6 \times 10^6$ and $W_1 = 3.3 \times 10^6$

$$R = \frac{6.6 - 3.3}{6.6 + 3.3} = 0.333$$

The loss of amplitude due to the reflection at the coal-shale interface is equivalent to about -10 dB.

The loss of amplitude due to internal absorption at 500 kHz is given by

$$\text{Attenuation} = 8.68 kx \quad (k = 2.3 \times 10^{-6} \text{ sec/in})$$

$$\approx 10 \text{ dB/in}$$

Hence, for a 500 kHz signal and a shale backing, Table A-2 gives the losses to be expected at various coal-layer thicknesses.

It is anticipated that signals from thicknesses greater than 3-4 inches may be too weak to properly detect. The main cause for loss in amplitude of the reflected signal is from internal absorption which can be reduced by using a lower frequency, e.g., 100 kHz. However, if the transmitted signal pulse is still 5λ in length, this means the pulse is 50 μsec wide. A 50 μsec pulse is equivalent to a round trip path in

Table A-2 - Signal Attenuation in Coal Mine Roof Thickness Measurements

| Z (in) | Losses for f = 500 kHz | | | |
|-----------|------------------------|------------|-------------|-------|
| | Absorption | Reflection | Beam Spread | Total |
| 1/2 (min) | 10 dB | 10 dB | --- | 20 dB |
| 1 | 20 dB | 10 dB | --- | 30 dB |
| 2-1/2 | 50 dB | 10 dB | --- | 60 dB |
| 3 | 60 dB | 10 dB | --- | 70 dB |

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coal equal to a thickness given by $z = \frac{v_c t}{2} = \frac{9.24 \times 10^4 \times 50 \mu\text{sec}}{2} = 2.3$ inches. Hence, the minimum resolvable distance at 100 kHz is about 2-1/2 inches. Table A-3 gives some attenuation losses to be expected for a test pulse with a characteristic 100 kHz frequency. At 100 kHz, the absorption loss is given by attenuation = 8.68 kfx = 2 dB/in. Some values for possible losses due to the beam spread were estimated; exact values are difficult to determine until a final transducer design and beam pattern is established.

It appears possible that the entire thickness range for the roof coal layer can be covered, but only by using two transducer units operating at two different frequencies selected to give continuous coverage.

Table A-3 - Signal Attenuation In Coal Mine Roof Thickness Measurements

| Z | Losses for f = 100 kHz | | | |
|--------------|------------------------|------------|-------------|-------|
| | Absorption | Reflection | Beam Spread | Total |
| 2-1/2" (min) | 10 dB | 10 dB | 5 dB | 25 dB |
| 10" | 40 dB | 10 dB | 20 dB | 70 dB |
| 12" | 48 dB | 10 dB | 25 dB | 83 dB |

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However, an interesting point was made at the progress review meeting with the Bureau of Mines in September 1971; there are two distinct applications for measuring the roof layer thickness. In one possible mine situation, it would be desirable to remove almost all of the coal from the roof while trying to avoid driving the continuous miner cutter into the roof rock. This would require measuring only thin coal layers. In the other mine situation, it would be desirable to leave some 4 inches to 10 inches of coal on the roof for roof control measures. This would require measuring thicker coal layers with no need to measure thin layers. Hence, it could be possible then to use only one transducer unit at a frequency fixed by the particular mining application.

In the application of the pulse reflection method to measuring the coal remaining on the floor of the mine, the worst case of underburden, clay, was chosen for analysis purposes. The reflection coefficient at the coal-clay interface is given by

$$R = \frac{W_2 - W_1}{W_2 + W_1}$$

where

$$W_2 \text{ (clay)} = 4.9 \times 10^6$$

$$W_1 \text{ (coal)} = 3.3 \times 10^6$$

$$R = 0.195$$

Hence, the reflection losses = $20 \log (0.195) = -14 \text{ dB}$.

Selection of a transducer resonant frequency of about 250 kHz would allow a thickness range of about from 1 inch to 5 or 6 inches (see Table A-4).

Table A-4 - Signal Attenuation in Coal Mine Roof Thickness Measurements

| Z | Losses for f = 250 kHz | | | |
|----------|------------------------|------------|-------------|-------|
| | Absorption | Reflection | Beam Spread | Total |
| 1" (min) | 10 dB | 14 dB | --- | 24 dB |
| 2" | 20 dB | 14 dB | --- | 34 dB |
| 5" | 50 dB | 14 dB | 6 dB | 70 dB |
| 6" | 60 dB | 14 dB | 6 dB | 80 dB |

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By keeping the signal amplitude losses from going over 70 to 80 dB and by using a reasonable acoustic power input to the transducer, it should be possible to detect the signal reflected from the coal-clay interface.

The thickness resolution using the reflection method is good. Since the transit time can be determined by the leading edge of the pulse, the time will normally be defined to within a quarter wavelength; thus at 100 kHz, $\lambda/4$ is equal to a Δt of 2.5 sec. In terms of coal thickness, the resolution then is

$$\Delta z = \frac{v\Delta t}{2} = 0.12 \text{ inch}$$

In summary, the acoustic pulse reflection method looks feasible for measuring coal thickness with the required resolution in a transceiver mode of operation, provided that a close contacting transducer arrangement is used, and provided that the roof coal-layer thickness measurements can be broken into two separate but adjoining ranges.

An alternate to having one transducer operate in a transceiver mode is the use of separate transducers for transmitting and receiving the signal. Either water jet or semi-direct coupling could then be used for the two transducer systems. However, the coupling for each unit

would have to be isolated from each other to prevent acoustic cross-talk; the generation of surface waves along the coal would have to be minimized or filtered to prevent interference with the true reflected signal.

APPENDIX A REFERENCES

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APPENDIX B
FUNCTIONAL DESCRIPTION OF ACOUSTIC-REFLECTION
ROOF/FLOOR COAL SEAM INTERFACE SENSOR

The content of this appendix was previously given in the Preliminary Design Review Document, "Feasibility of Remote Control and Development of Remote Control Devices and Sensors, Vol. 2, Continuous Mining Machine Seam Interface Sensors," Bendix Report No. 6040, November, 1971. It is repeated here for completeness of this report. The system described here was not built due to problems encountered which are described in the body of this report.

The system used to measure the coal thickness remaining to the seam interface at the roof and floor consists of essentially four separate subsystems: (1) the transducer sensor, (2) the sensor mounting system, (3) the electronics, and (4) the display console.

The present model of the sensor system will not be mounted and demonstrated on a continuous mining machine during this contract period. However, in the final model envisioned, a mechanical mechanism would bring an acoustic transmit and receive sensor unit into contact with the coal surface at the roof or floor in a location as near to the working face as possible. The mechanism would keep the sensor units in contact with the roof or floor during operation of the continuous miner, allowing for normal vibrational movement of the miner. A continuous flow water coupling between the transducers and coal surface will provide good acoustic contact to the coal as well as a surface cleaning action of flushing away coal dust. For the floor thickness sensor, a floating plow is visualized ahead of the sensor unit to clear away large debris and to prevent loose coal pieces from interfering with the sensor unit.

An electrical voltage pulse triggered by the electronics is applied to the piezoelectric transducer element, and converted by the

transducer into an acoustic signal several oscillations in width, which then enters into the coal layer. When the acoustic signal reaches the interface between coal and the adjoining strata, part of the signal is reflected back because of the acoustic impedance difference between the two layers. This reflected signal returns to a receiver transducer where the acoustic energy is converted back into an electrical signal. The received signal is processed by the electronics to determine the time delay between transmission and detection. This time interval (t) between the transmitted and returned signal, which is related to the coal thickness (z) by $z = vt/2$, is then converted into an electrical output that is proportional to the determined coal thickness. Provision is also made to allow for calibration adjustments for variations in the coal velocity (v). The signal output from the electronics subsystem is used to drive a meter on the display console so that the continuous miner operator (on-board or remote) may respond to the changing coal thickness in the roof and floor.

The inclination or declination of the coal seam would also be determined in an operational system. Two separate sensor units, one located on each side of the continuous miner for the roof, and another set located likewise for the floor would be used. A pair of readings from either the roof or floor sensors would then give the thickness of the layer on each side of the miner; any differences in these readings would determine the slope of the interface normal to the direction of the mining machine.

In addition, the slope of the interfaces in the direction of travel of the miner may also be determined if an electronic memory bank is included, along with an additional input specifying the amount of forward motion of the miner between successive sets of readings.

APPENDIX C
ACOUSTIC AVERAGING TECHNIQUE FOR
DETECTING COAL-SEAM INTERFACE

Coal mines similar to the one encountered during the experimental field test at Old Ben Coal Mine #24 contain many foreign impurity layers in the bulk of the head coal. In these types of mines, it was found that both cracks and impurity layers were random in length in any given direction, and were randomly distributed within the coal volume. On this basis, a technique is suggested which averages the acoustic reflected signals over a distance large compared to the mean length of cracks and impurity layers. Large, in this case, may be between five to ten times the crack length. In this manner, random reflections will be averaged out to small values, while the coal/shale boundary reflection will approach a finite mean value. Furthermore, to avoid averaging non-pertinent reflections in the received signal, only that immediate portion of the received signal exhibiting the coal/shale boundary signal will be averaged.

A block diagram of the proposed system is shown in Figure C-1. The transmitting and receiving transducer sensor assembly is attached to the CMM. The heading of the CMM is controlled by a human driver, who monitors the coal/shale depth readout. The coal/shale boundary depth is initially determined by mechanical means, and the value is fed into the gate centering circuitry. This centers a range gate window about the reflected coal/shale boundary signal. The gated received signal is then fed into a signal averager, which computes a running average. As the CMM moves and the received signal is averaged, reflected signals from newly encountered cracks and impurity layers will begin to average upwards, while similar previous signals will average downward. However, with a sufficiently long averaging time, the coal/shale reflected signal will persist at a higher average value.

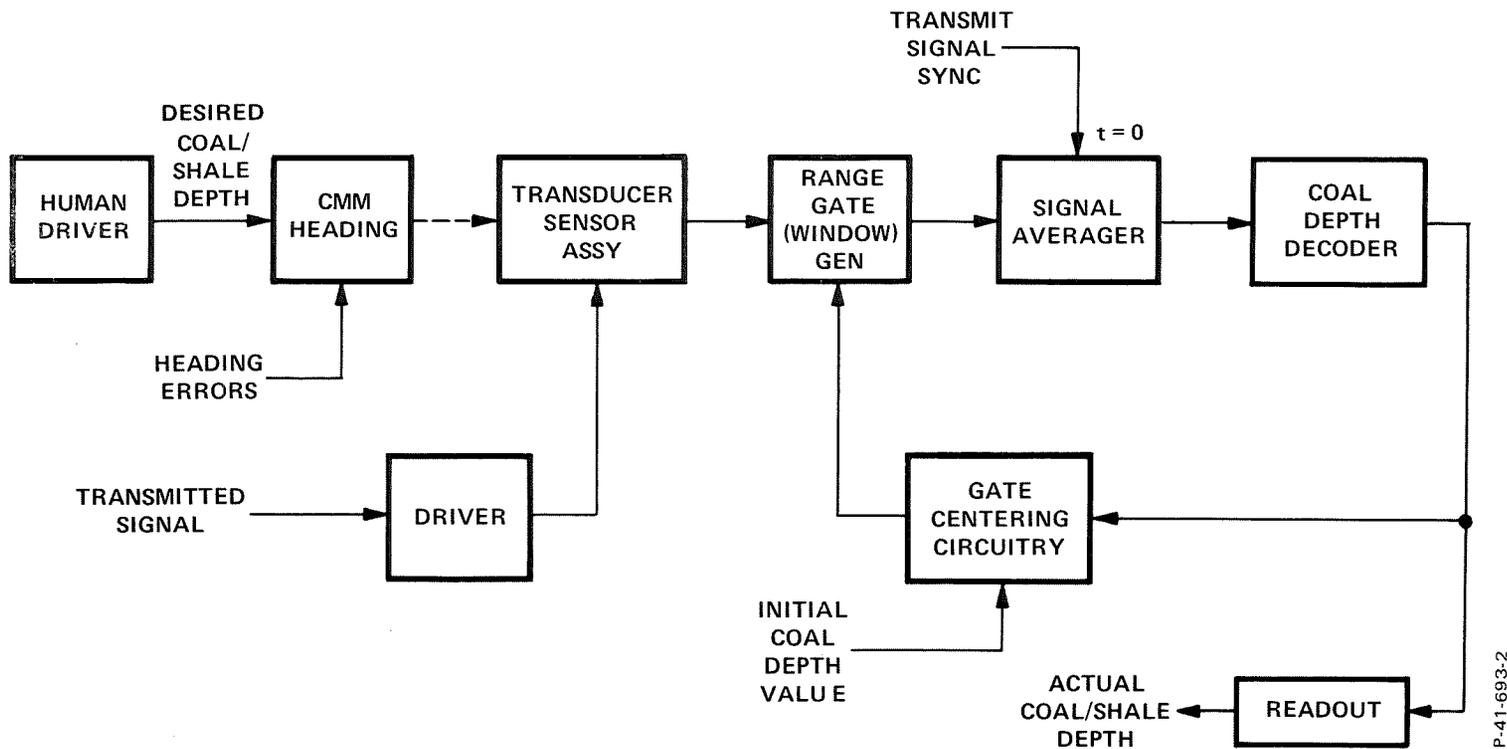


Figure C-1 - Acoustic Signal-Averaging Coal Depth Sensor Technique

Because the CMM heading will not always be parallel to the coal/shale boundary, its reflected signal will tend to move off the center of the window. The centering circuitry will continuously adjust the window position to hold the coal/shale reflected signal in the center. A readout of the actual coal depth will be provided to the human driver. The system could employ transmission of a single-cycle signal of given frequency or waveshape, or an FM chirp signal. This would depend upon which gave the better statistical average. In order to better average out the random crack and impurity layer reflections, it is also possible to resort to multiple transducers.

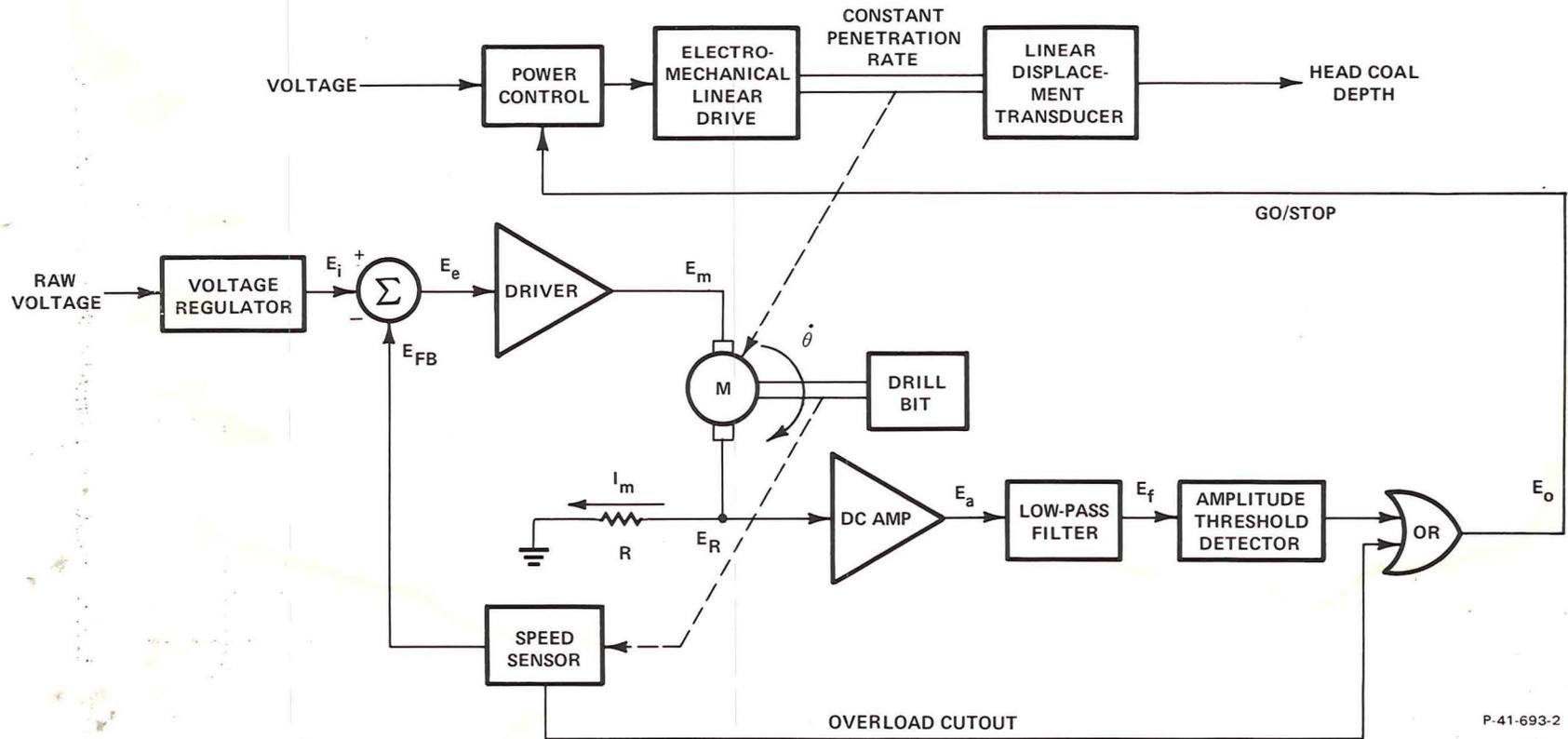
In conclusion, an acoustic signal-averaging technique appears to be possible even in the midst of cracks and impurity layers within the head coal. The only requirements are: (1) the cracks and impurity layers must be random; (2) they must have a mean length less than the mean cyclic undulations of the coal/shale boundary; and (3) the head coal depth must be initially determined by an independent means.

APPENDIX D
MECHANICAL DRILL TORQUE SENSING TO
DETECT COAL SEAM INTERFACE

A mechanical scheme is recommended for consideration to measure the depth of coal to the coal/shale interface. Mechanical methods can be practical under certain mining conditions, for example, when the CMM is not in constant motion. The approach is to sense a change in load torque on a constant speed motor driving a drill bit at a constant penetration rate through the coal and into the shale. Compressive strength of rock and coal is recognized to be one of the significant parameters providing a measure of the borability of these materials.* The compressive strength of shale can range anywhere between 2 to 68 times that of coal. Limestone compressive strength can vary between 1 to 74 times that of coal. Thus, the higher compressive strength of shale, compared to coal, requires a higher drill motor torque to maintain the same speed and penetration rate in shale as in coal. A system incorporating this approach is shown in Figure D-1. A regulated voltage E_i represents the reference input to the system. Recall that motor torque T is directly proportional to motor current I_m . Thus, a small resistor R is placed in series with the motor in order to measure I_m from the relationship

$$I_m = \frac{E_R}{R}$$

* J. P. Carstens, "Heat Assisted Tunnel Boring Machines," Report No. PB197243, United Aircraft Corp. E. Hartford, Conn., September 1970; P. J. Huck and M. M. Single, "Rock Fracture by High Speed Water Jet," Report No. FRA-RT-71-58, DOT Contract FR-9-0031, IIT Research Institute Technology Center, Chicago, Ill., December 1970.



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Figure D-1 - Mechanical Approach to Measurement of Head Coal

where E_R is the voltage across resistor R. The voltage E_R is fed into a dc amplifier to give voltage E_a , which is proportional to I_m and thus load torque. Meanwhile, the motor shaft driving the drill bit is also coupled to a speed sensor which generates a voltage E_{FB} proportional to motor shaft angular velocity ($\dot{\theta}$). This voltage E_{FB} is compared against the reference input E_i to produce an error voltage E_e . E_e is then amplified by the driver to generate the motor drive voltage E_m , which holds the drill speed constant with fluctuating load. The motor and drill assembly are driven into the coal and shale at a constant penetration rate by an electromechanical linear drive. The dc amplifier output voltage E_a will contain fluctuations due to hard spots and impurity layers in the coal. These are smoothed out by the filter to give voltage E_f . This is illustrated in Figure D-2. When the drill bit reaches the shale, then the torque, and thus E_f , will rise to a new level and stay there. The absolute values of E_f for coal and shale may vary with drill bit wear. However, the relative difference will

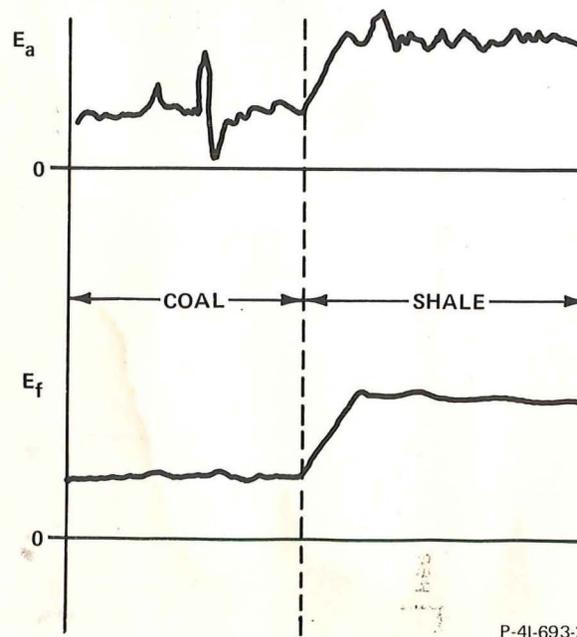


Figure D-2 - Representative Signals From Mechanical Approach

probably not change much. E_f is then fed to an amplitude threshold detector, which provides a GO or STOP signal to the linear drive. OR gated with the threshold detector output is an overload cutout signal from the speed sensor. If the load torque should ever become excessive, the drill speed would drop below a preset minimum value. This would signal the linear drive to STOP, and prevent breakage of the drill bit.

The distance that the drill has penetrated the coal is measured by a linear displacement transducer to give the head coal depth. This system should be inexpensive and adaptable to mounting on the CMM. The mechanical design would be simplified by halting the forward progress of the CMM during a coal depth measurement. This should not present an operational problem for the CMM since these measurements need not be made often; one measurement every two feet should be sufficient. The reason for this is that this method of measurement is absolute at each point and does not require any averaging.

One problem area associated with this, or any mechanical drilling technique, would be the existence of very hard impurity layers (for example, iron pyrite) in the head coal. If the hard layers were sufficiently thick, it would be difficult, if not impossible, for the drill to penetrate the layers. The result, of course, would be an erroneous thickness measurement.