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FM-CW ELECTROMAGNETIC TECHNIQUE OF MEASURING COAL LAYER THICKNESS

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U.S. Bureau of Mines
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Edward O. Vetter, Under Secretary
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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Acting Director

FOREWORD

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FM-CW ELECTROMAGNETIC TECHNIQUE OF MEASURING COAL LAYER THICKNESS

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ABSTRACT

An FM-CW microwave system was investigated for measuring coal layer thickness. Measurements were made in three different mines near Pittsburgh, Pennsylvania, near Fairview, West Virginia, and near Coffeen, Illinois. Microwave frequencies in the range 1-2 GHz were used to measure samples up to 55 cm thick. All samples were backed with a naturally occurring shale. Measurements were also made on coal and shale samples compounded in the laboratory at the Bureau of Mines Pittsburgh Mining and Safety Research Center near Bruceton, Pennsylvania.

The results indicate that layer thickness can be determined in most cases, although large anomalies may, in some cases, produce misleading results. Many anomalies that were detected with the FM-CW system were verified visually by drilling into the coal layer.

The dielectric constant of coal apparently varies significantly within a coal seam.

The form of the output signals from the FM-CW system seem to simplify the data interpretation and analysis process as compared to the manually swept microwave system used previously. It appears that this technique has the potential of measuring changes in the dielectric constant of a coal seam and providing an output that can be used for real-time corrections in layer thickness measurement.

Key words: Automation; coal; coal mine safety; dielectric constant; energy; microwave measurement; nondestructive testing; thickness of coal layer.

1. INTRODUCTION

The possibility of using a microwave system to measure coal layer thickness in a mine was investigated by August 1974, and the results were reported in NBSIR 74-387, Microwave Measurement of Coal Layer Thickness, dated September 1974. The basic measurement capability was demonstrated in that microwaves penetrated the coal and were reflected by a shale background.

The primary objectives of this phase of the proposed effort were to develop improved methods for microwave measurement procedures, to determine the thickness of undisturbed coal layers in situ, and to demonstrate these procedures in actual mines.

2. MEASURING SYSTEM

The microwave hardware used in these experiments was basically the same as that used previously [1]; however, the antenna design was modified to provide better directivity and to decrease the coupling between transmit and receive antennas over the frequency bandwidth. Details of these modifications will be presented later in this report.

Appropriate microwave plug-in units were acquired to minimize the quantity of electronic equipment needed for in-mine experiments, and the entire system was powered from a 12 Vdc automobile battery. Data recording was done with a magnetic tape recorder and, in some cases, with an X-Y plotter.

The fundamental difference between the system used previously and the one used for this work is that a greater degree of data processing was accomplished in real time prior to recording. The microwave system was operated as a frequency modulated-continuous wave (FM-CW) radar.

The microwave signal generator in figure 1 is swept in frequency over its bandwidth so that a linear frequency vs. time output signal is produced.

The microwave signal travels from the generator to the mixer via more than one path. If the electrical lengths of the paths are identical, the reference and test signals going into the mixer would arrive at the same time and the instantaneous rf frequencies would be identical at all times.

But the test signal will arrive at a later time because that signal goes through the antennas via the coal sample. A portion of the test signal is reflected at the air-coal interface and another portion is reflected at the coal-shale interface. These reflected signals will arrive at the mixer at times t_2 and t_3 respectively as shown on figure 1.

Because all inputs to the mixer arrive at different times, the instantaneous microwave frequencies differ. The mixer is a product demodulator and has an output that is a function of the product of the inputs. Only the lowest frequency components in the output are preserved; the higher frequencies are filtered out.

The lower frequency components are displayed on a spectrum analyzer. The location of the first peak is a function of the distance from the antennas to the coal surface. The location of the next peak is a function of that distance plus the coal layer depth and its dielectric constant.

Assume for the moment that the microwave signal is incident upon an infinitely thick layer of coal. Let the reference signal arriving at the mixer be presented as

$$e_1 = E_1 \cos \omega_{(t)} t, \qquad (1)*$$

and the test signal reflected from the coal surface as,

$$e_2 = \Gamma_1 E_2 \cos\left[\omega_{(t)} (t + \frac{2R}{c})\right], \qquad (2)$$

where 2R/c is the time required for the signal to travel a distance R from the transmitting antenna to the coal surface and back to the receiving antenna. It is assumed that both antennas are equidistant from the coal surface and that the angle of incidence is zero degrees.

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*See appendix for definition of terms.

Going through the product demodulation process and neglecting the harmonic microwave frequency component, the mixer output signal is,

$$e_0 \simeq \frac{\Gamma_1 E_1 E_2}{2} \cos \omega_{(t)} \frac{2R}{c} . \tag{3}$$

Letting,

$$\phi_{(t)} = \omega_{(t)} \frac{2R}{c} , \tag{4}$$

the frequency of the signal out of the mixer is,

$$f_0 = \frac{1}{2\pi} \frac{d\phi_{(t)}}{dt} , \tag{5}$$

$$f_0 = \frac{2R}{c} \frac{df_{(t)}}{dt} . \tag{6}$$

If the frequency of the microwave signal is changed at a constant rate, the frequency of the signal out of the mixer is proportional to the distance from the antennas to the coal surface.

Extending the analysis to include a finite layer of coal comprised of the air-coal surface and the coal-shale surface, the total received test signal [2] is,

$$e_r = E_2 \left(\frac{\Gamma_1 + \Gamma_2 e^{-2\gamma d}}{1 + \Gamma_1 \Gamma_2 e^{-2\gamma d}} \right) e^{-j\omega_{(t)} \left(t + \frac{2R}{c}\right)} \tag{7}$$

Recognizing that coal is a lossy microwave material and utilizing typical dielectric constants of coal ($\varepsilon = 5$) and shale ($\varepsilon_s = 36$), the amplitude of the denominator in eq. (7) is found to be approximately unity. Thus neglecting the multiple reflection terms contributed by the higher order reflection term in the denominator, eq. (7) can be written as [2]

$$e_r \simeq \Gamma_1 E_2 \cos \left[\omega_{(t)} \left(t + \frac{2R}{c} \right) \right] + \Gamma_2 E_3 \left\{ \cos \left[\omega_{(t)} \left(t + \frac{2R}{c} + \frac{2d\sqrt{\varepsilon}}{c} \right) \right] \right\} e^{-2\alpha d} \tag{8}$$

Mixing this received signal with eq. (1) will provide a mixer output signal

$$e_0 \simeq \frac{\Gamma_1 E_1 E_2}{2} \cos \left(\omega_{(t)} \frac{2R}{c} \right) + \frac{\Gamma_2 E_1 E_3}{2} \left\{ \cos \left[\omega_{(t)} \left(\frac{2R}{c} + \frac{2d\sqrt{\varepsilon}}{c} \right) \right] \right\} e^{-2\alpha d} \tag{9}$$

when the harmonic microwave signal is neglected.

The frequency of the first component is given by eq. (6) and the frequency of the second component is

$$f_{02} = \left(\frac{2R}{c} + \frac{2d\sqrt{\varepsilon}}{c}\right) \frac{df_{(t)}}{dt} . \quad (10)$$

The difference between eqs. (10) and (6) is a frequency that is proportional to the thickness and the electrical properties of the coal layer.

$$\Delta f_0 = \frac{2d\sqrt{\varepsilon}}{c} \frac{df_{(t)}}{dt} . \quad (11)$$

The procedure has been to measure the dielectric constant, ε, on site and reduce the working equation to one unknown, d, the coal layer thickness.

$$d = \frac{c}{2\sqrt{\varepsilon}\ df_{(t)}/dt} \Delta f_0 . \quad (12)$$

It has been found that more than one finite layer of coal may exist at a given point in a mine. The analysis given here for one layer may be extended for stratified media.

3. SYSTEM PARAMETERS

Equation (12) is the working equation for the FM-CW system. Based upon the measurements made last year [1] and anticipating that up to 40 cm of coal will be measured again, the microwave frequency band 1-2 GHz was used. That bandwidth was swept in 7.48 milliseconds thus eq. (12) becomes

$$d = 0.1122 \frac{\Delta f_o}{\sqrt{\varepsilon}} , \ (cm) \quad (13)$$

This equation contains two unknowns (d, ε) both of which will be determined by measurement.

A measured value for the dielectric constant (ε) can be obtained for the coal by any of the three techniques discussed in [1]. The difference frequency (Δf_0) out of the mixer is also a measured value; thus, the layer depth (d) is calculated from eq. (13).

A sample of raw data obtained with the system at one of the test points is shown in figure 2. The high amplitude response at 8.05 kHz is the reflection from the air-coal interface. The low amplitude ripple preceding that response was caused by imperfections in the microwave system, such as residual mismatch reflections in the components. The response at 8.4 kHz was caused by reflections from a sulphur ball (pyrite concretion) within the coal seam at that particular measurement point.

The response at 8.9 kHz was caused by reflections from the coal-slate interface. The measured dielectric constant for the coal at that test point was 7.6. Using this with the difference frequency from figure 2 in eq. (13), the depth of the coal seam at that test point is 34.6 cm. The physical thickness measured at that test point was found to be 36.8 cm.

The physical distance between the sulphur ball and the shale at that test point is 20 cm. In discussions with some of the miners in that particular mine it was learned that a thin layer (up to 0.6 cm thick) of impure coal exists about 20-25 cm below the coal-shale interface throughout the Pittsburgh seam. The impure coal layer is referred to as the "top binder," or the "soot layer." It was noted that many dielectric discontinuities, such as sulphur balls and shale lenses, occur at the top binder level.

4. ANTENNA IMPROVEMENT

The theories developed for all microwave measurements in coal mines assumed ray paths for the electromagnetic energy radiated from the antennas. It was realized that the antennas used were not directive enough to fully justify use of a single ray model; however, in the initial measurements last year the antennas were selectively positioned in the mine to reduce undesired direct coupling.

A portion of the effort this year was expended in improving the directivity of both antennas and providing better isolation between them. Improvements like this decrease the susceptibility of the system to spurious reflections from surrounding obstacles.

The antennas are broadband rectangular aperture horns which utilize double ridged waveguide techniques [3]. Initially two sides of the horns were made from a printed circuit board. These were removed and replaced with solid aluminum to reduce the H plane beamwidth. All the mechanical junctions in the horn assembly were taped with conducting tape to provide continuous current paths inside the horn and to minimize current leakage and resulting spurious radiation. Both antennas were covered externally with rf absorbing material to minimize the effect of spurious radiation caused by current flowing on the outside of the antennas.

Finally, because in an operational mine the horns will be pointed up, it was realized that some type of dust cover would be necessary to prevent filling the horns with coal dust. A lucite lens was designed and evaluated for satisfying two purposes. First, it would cover the entire aperture and would serve as a dust cover, and second, it would serve to focus the radiated energy and more closely validate the ray theory assumption. Two different lens designs were evaluated. One has a radius of 7.5 cm and the other had a radius of 10 cm.

The performance characteristics of the antennas were determined by measuring radiation patterns at 1 and 2 GHz in an anechoic chamber. The intent was to make comparative field strength measurements. Results of the antenna measurements are shown in figures 3 and 4. The narrowest beamwidth and the lowest level sidelobes occur when the 10 cm radius lens was flush mounted on the aperture. Thus a 10 cm radius lens was fabricated for each antenna.

Figure 5 is a photograph of the antenna assembly positioned under a test area in the Bruceton mine.

5. EXPERIMENTAL RESULTS

5.1 Laboratory Samples of Shale and Coal

The Bureau of Mines had prepared samples of a coal layer on a shale layer. The shale layer was comprised of 92 percent (by volume) shale dust and 8 percent cement. These were mixed with water and poured into a form. Similarly a 92 percent coal dust and 8 percent cement mixture was prepared and poured on top of the shale.

Several different laboratory samples were measured by placing the FM-CW system antennas above the samples. A summary of sample size and measured results are given in table I.

Sample I was the only one considered to have sufficient surface area for measurements with the FM-CW system. Nevertheless, all of the measured results obtained from those samples are given on Table I. With samples 2, 3, and 4, the FM-CW system illuminated not only the desired coal surface but also the floor and, in some cases, other samples adjacent to the one being measured. Thus, undesirable responses complicated much of the data collected. Most of the undesired responses were related to their sources at the time of the measurement with the use of a small metallic reflector.

The dielectric constants for samples 1, 2 and 4 were measured using return loss techniques. Those values, along with the FM-CW frequency output, were used in eq. (13) to arrive at the tabulated layer thickness.

No return loss measurement was made on sample 3. The measured dielectric constant values for sample 3 were determined by using the physical depths of the coal and shale along with the measured difference frequencies in eq. (13).

Moisture contents (by weight) for these samples were measured by the USBM [4]. Two specimens were chipped from each sample for laboratory moisture analysis. Average results are shown in parenthesis on table I.

5.2 Bruceton Mine

As was done last year [1], an existing mine face was undercut from the mine floor up toward the shale to prepare three test areas having different roof coal depths. The physical arrangement is shown in figure 6. Figure 7 is a photograph of the total area, with the FM-CW system in the foreground between the miners. The undercut extended approximately 1.25 meters into the coal face so that the antennas could easily be placed under each test area. Each test area was at least 1.25 meters wide. The coal surfaces were dry.

The dielectric constant was measured in the three test areas by using the measured difference frequency and the physical depth in eq. (13). A summary of that dielectric constant data is given in table II.

As was done last year, the dielectric constant was also measured by utilizing known step changes in coal depth, when the absolute coal depths are not known. Let a difference frequency measurement be made in one of the test areas of figure 6. Equation (13) can be rearranged into the form,

$$\Delta f_1 = 0.1122\ d_1\sqrt{\varepsilon}. \tag{14}$$

Now let a difference frequency measurement be made in another of the test areas of figure 6. The equation for that measurement becomes,

$$\Delta f_2 = 0.1122\ d_2\sqrt{\varepsilon}. \tag{15}$$

Taking the difference between eqs. (14) and (15) and solving for the dielectric constant results in

$$\varepsilon = \frac{79.4(\Delta f_2-\Delta f_1)^2}{(d_2-d_1)^2} \tag{16}$$

After the dielectric constant has been determined with eq. (16), it can be used in eqs. (14) and (15) to calculate the depths of the head coal at those test points.

This measurement and data processing procedure was utilized in the Bruceton mine. A summary of the results are given on table III.

The results given on tables II and III are calculated from data collected at various points along approximately 3 meters of the face. This year, as was observed last year, there was some variation in the dielectric constant data. It is believed that the variation is real and is caused by variations in the constituency and homogeneity of the coal along the seam. For example, the coal in test area 3 appeared to have a 17.7 cm lower layer of friable coal, as observed on site. The upper 22.9 cm of coal was harder. Such stratification was noted last year also in the Bruceton mine [1], and is consistent with the location of the "top binder" in the Pittsburgh seam.

It was also noted that although the coal surfaces and the floor under the undercut were dry, some water was dripping from the roof 1.25-1.5 meters back from the coal face. Variable amounts of moisture within the coal at the various test points can result in different dielectric constants.

The head coal depth is related to the dielectric constant as given in eq. (13). Variations in the dielectric constant will produce errors in the measured depth unless those variations are taken into account. The relative magnitude of the error can be determined by differentiating eq. (13) with respect to $\sqrt{\varepsilon}$, and utilizing the change in dielectric constant.

$$\frac{|\Delta d|}{d} = \frac{1}{d} \frac{\partial d}{\partial \sqrt{\varepsilon}} |\Delta \sqrt{\varepsilon}| \ . \tag{17}$$

After going through the differentiation, eq. (17) becomes

$$\frac{|\Delta d|}{d} = \frac{|\Delta \sqrt{\varepsilon}|}{\sqrt{\varepsilon}}. \tag{18}$$

Using an average value for $\sqrt{\varepsilon}$ and the variation from tables II and III in eq. (18), the error in the depth calculation can be as high as approximately 4 percent.

Much larger variations were noted in subsequent measurements in another mine; thus, a method has been devised for the FM-CW system to continuously monitor the dielectric constant. That method will be discussed in the next section.

5.3 Loveridge Mine

5.3.1 Roof Data

Measurements were made at a site where the coal had been mined at least six years ago. The actual site was also used by Foster-Miller Associates, Inc., for roof coal measurements with a pulse radar (USBM Contract No. H0357000). That site was approximately 17 meters (55 feet) long. Measurements of the roof coal depth were made with the FM-CW system every 1.5 meters (5 feet) along the test site.

A physical analysis of the test site was conducted jointly with Mr. Gregg Riley of Foster-Miller Associates, Inc., immediately after the electromagnetic measurements were done. This analysis consisted of drilling 4 cm (1 5/8 inch) diameter holes into the coal layer at approximately 1.5 meter intervals along the test site to visually and physically note the constituency, stratification, and thickness of the coal layer. Core samples of 10 cm diameter were taken at stations 20 and 30 for moisture analysis.

Mr. Riley has recently completed a survey of the test site by using a 4 cm diameter probe drill at approximately 30 cm intervals to determine stratification and thickness of the coal layer. He has provided us with a copy of those results and it has been decided that those should be used as the reference data for the FM-CW measurement.

The results obtained in the Loveridge experiments are shown in figure 8. The radar data have been corrected for apparent changes in the dielectric constant of the coal along the test site. Changes in dielectric constant were measured as a function of changes in the amplitude of the signal reflected at the air-coal interface. Because no automatic gain control circuits were used in the system, a condition external to the measurement system must cause the amplitude of the coal surface response to vary. As shown previously [1], the amplitude of that signal is a function of the dielectric constant of the coal. Thus the changes in the amplitude of the coal surface reflected signal correspond to changes in the coal dielectric constant used in (13). A tabulation of delectric constants measured over the test sight is given in table IV.

The received signal amplitude for the coal surface response is shown on figure 9. The plots for the two experimental days run essentially parallel at all except station 40. Parallel responses indicate that the receiver responded to the same change in coal dielectric constant both days but the receiver gain was set at different, but constant, levels.

Moisture analysis of samples taken from stations 20 and 30 show the coal to be relatively dry [5], which is consistent with the lower dielectric constants measured at those stations.

Near the end of the first experimental day the roof area of station 40 was soaked with water in conjunction with an experiment being conducted by Foster-Miller Associates, Inc. The water was sprayed on the roof after the FM-CW amplitude responses on figure 9 were obtained.

It was noted the following morning that the roof area was still wet. A higher received signal amplitude on figure 9 corresponds to a higher dielectric constant. Addition of water to a coal sample would increase the dielectric constant; thus, the received signal amplitude data seems to correlate well with the sequence of experimental events.

Not shown on figure 8 are other microwave responses, some of which correlate with the "top binder" and other discontinuity locations. Other of the microwave system responses probably were caused by discontinuities that were undetected during the physical analysis.

The sample of raw data shown in figure 2 was one of the most straightforward to analyze. Many of the data were that straightforward; however, some were more complicated. Consider the data shown in figures 10 and 11 for example. For figure 10, the closest physical analysis drill hole for station 10 was at station 11. That analysis showed that a thick sulphur ball was located 17.1 cm up from the coal surface and was 13.4 cm thick. An additional 12.7 cm layer of coal existed above the sulphur ball.

In figure 10, the 8.15 kHz response corresponds to the reflection at the coal surface. The response at 8.5 kHz, along with the measured dielectric constant at station 10 (ε = 5.2) indicated that a reflection occurred 17.2 cm in from the coal surface. That distance correlates very well with the noted location of the lower edge of the sulphur ball; thus, it is concluded that 8.5 kHz response was indeed caused by the sulphur ball. It probably lies on the plane of the "top binder."

Because the sulphur ball was noted to be 13.4 cm thick at the drill hole point, it is quite likely that the response at 8.9 kHz was caused by a reflection at the top of the sulphur ball. Using a dielectric constant measured for shale in the mine (ε = 24.2) along with the difference frequency of 0.4 kHz (8.9 8.5 kHz) results in a FM-CW measured thickness of 9.3 cm.

Finally, the frequency response at 9.2 kHz was probably caused by reflection at the coal-shale interface. The thickness of the coal above the sulphur ball was computed to be 13.4 cm, giving a total depth from the coal surface to the shale at 39.9 cm at station 10.

For figure 11, the closest physical analysis for station 15 was done at station 14, where the total physical thickness of the coal was 52.1 cm. The response at 8.45 kHz corresponds to a reflection at a depth of 17.2 cm. Based upon all the data analyzed and considering the relatively large amplitude of that response, it is assumed that reflection was caused by the top binder.

The weak response at 8.7 kHz corresponds to a reflection at 30.4 cm within the coal layer. No discontinuity was noted at that depth in the physical analysis at station 14.

The large amplitude response at 9.1 kHz is interpreted as the reflection at the coal-shale interface, thus the total coal thickness is found to be 52.6 cm at station 15.

In both of these examples the response from the coal-shale interface is quite definite; however, there can be some problems in interpreting all of the responses without a complete physical analysis. This measuring system can be readily adapted to continuous recording and then some of the anomalies such as sulphur balls become obvious because they are small in extent.

5.3.2 Floor Data

Figure 12 is data taken with the FM-CW looking into the floor. There was no coal on the floor at any point, except for some dust that was mixed with rock and shale dust at station 40.

The data indicates that some floor layering is present. A very limited physical analysis revealed the following.

No coal was on the floor at station 50. The first 16 cm of slate was easily fractured and very easy to remove. At a depth of approximately 16 cm, the slate become very hard and was essentially impenetrable with a hand pickax. Most of the excess water that was sprayed on the roof the previous day collected on the floor at station 50. Water penetrated the shale approximately 2.5 cm.

Approximately 1 cm of coal, shale, and rock dust was on the floor at station 40. This was the only point where floor coal in any form existed. The first 2.5 cm of slate fractured very easily and was removed. The hard slate layer came next. No water collected in this test area.

At station 30, 6.5 cm of shale and rock dust was on the surface. A 5.0 cm layer of easily fractured shale came next followed by the hard shale. The entire area was dry.

At station 10, the upper 7 cm of slate was easily fractured. This was followed by the hard slate. The entire area was dry.

5.4 Hillsboro Mine

Measurements were made at a site where the coal had been mined 4-6 week previously. This site was also used by Foster-Miller Associates, Inc., for measurements with their pulse radar. This site was approximately 31 meters (100 feet) long. Measurements were made every 1.5 meters (5 feet) along the test site.

A physical analysis of the test site was conducted jointly with Mr. Riley of Foster-Miller Associates Inc. This analysis consisted of drilling 4 cm diameter holes into the coal layer at approximately 30 cm intervals along the test site to visually and physically note the consistency, stratification, and physical thickness of the coal layer. Samples were taken for moisture content analysis in the laboratory [5].

The results obtained from these experiments are shown in figure 13. In these experiments also the amplitude of the signal reflected at the air-coal interface was noticed to vary from test point to test point; however, the range of variation at Hillsboro was much greater than that at

Loveridge. Perhaps the wider range of variation at Hillsboro is attributed to the fact that the coal layer thickness ranged from essentially zero to approximately 20 cm, thus the dielectric constant at the surface ranged from values of slate to values of coal. In any event, the wide range of amplitude variation drove the spectrum analyzer response off scale at times. This large change in received signal strength was counteracted on site by adjusting the system gain. Changes in system gain were not recorded, thus the measured results shown on figure 13 are not corrected for changes in dielectric constant. A dielectric constant of 4.6 was used for all the results given in figure 13.

Another problem that was present with these experiments (not realized until the data was being processed) was that the system had not been set up for very thin coal layers. The rf sweeper used had the capability to be swept over the bandwidth 2-4 GHz. For coal depths less than 10 cm the rf bandwidth should have been increased to increase the system resolution. Thus, measured data was not obtained at all of the thinner test points.

6. CONCLUSIONS

6.1 The FM-CW system can be used to measure the thickness of a layer of coal under most conditions, as well as detect other anomalies within that layer. The thickest layer measured with this system was 55 cm. However, that does not appear to be the upper limit.

6.2 The FM-CW system provides an output signal in a format that is amenable to data interpretation and analysis processes. Information other than coal thickness is inherently present in the data output. The distance from the antennas to the coal surface, for example, can be extracted. Anomaly presence is also indicated.

6.3 The dielectric constant of coal apparently varies significantly within a coal seam. The dielectric constant in the Bruceton mine was lower this year than last year. Last year the coal surfaces were wet because of the high humidity within the mine. This year the coal surfaces were dry; thus moisture was evidentally a significant factor in those measurements.

6.4 This FM-CW measurement technique has the potential of continuously measuring changes in the dielectric constant of a coal seam and providing an output signal that can be used for real-time measurement of layer thickness. It should be pointed out, however, that this measurement is related to the dielectric constant of the coal at the surface. It is believed that for measurements near the face in operational mines a measure of the dielectric constant near the surface of a layer of coal should be representative of that for the entire layer at that point.

6.5 The realization of the existence of the "top binder" in the Pittsburgh seam immediately explained some of the "spurious" responses last year in the initial experiments as well as this year. The fact that the top binder varies in thickness from essentially zero up to 0.6 cm indicates the ability of the FM-CW system to respond to thin layers whose physical and electrical differences from the surrounding coal are very slight.

6.6 The dielectric constant and thickness of several laboratory prepared samples of coal were measured; however, only one sample was considered to have sufficient surface area for measurements with the radar system.

6.7 The directivity of both antennas and the isolation between them was improved by the use of lenses and by taping the mechanical junctions to provide continuous current paths.

6.8 The presence of sulphur balls, shale lenses, and other dielectric discontinuities within a coal layer can complicate the data output from the system and consequently its analysis. Most of those discontinuities are small in extent and will only temporarily appear in the data output. In an operational system the coal removed may extend above the top binder; thus many of the discontinuities will be removed prior to measurement.

6.9 Floor data were collected at several points in the Loveridge mine. The data indicates floor layering; however, a detailed physical analysis of the floor was not done. No coal was on the floor where these measurements were made.

6.10 Penetration of the shale layer with the microwave signal was accomplished last year. The results obtained this year also indicate penetration of the shale layer; however, a physical analysis of that layer was not done. Shale layer data may be useful to delineate the layering within the shale and for guidance during roof bolting operations.

6.11 The FM-CW technique is much more amenable to automation than the technique used last year.

7. RECOMMENDATIONS

A program could profitably be undertaken to develop and apply this microwave measurement technique. The following specific efforts are recommended for advancing the technology toward developing a practical, reliable coal interface detector (CID) to determine coal-shale interface distance into the roof and the floor for anomaly detection and for distance measurements.

7.1 Instrumentation effort. This effort would be aimed at obtaining a fully automated, permissible system. The starting point would be the FM-CW system as it now exists; however, some modifications should be done in attempts to simplify this existing design. For example, the system should be modified for one antenna experiments that would, if successful, simplify the amount of hardware required for an operational system. This will involve use of state-of-the-art directional couplers. Solid state microwave sources in the frequency range 1-4 GHz should be selected for incorporation into a permissible system. Appropriate solid state circuitry must be developed to process the microwave system output and to display the coal layer thickness on a continuous basis.

7.2 Material properties measurement effort. The objective is to measure the permittivity of coal, shale, sulphur balls, etc., in mine environments and with laboratory samples from operational mines to determine the ranges of dielectric constant values encountered in situ. Included here is a determination of the magnitude of changes of dielectric constant caused by localized conditions in a mine particularly near the front face where actual conditions occur in an operational mine.

7.3 The penetrability of electromagnetic signals into the front face of a stratified coal seam should be studied to determine the feasibility of detecting sulphur balls, shale lenses, and other anomalies up to 1 meter ahead of the front face. Knowledge of the electrical properties of sulphur balls and shale lenses with respect to the surrounding coal is of importance in this effort. Those materials must continue to be studied in situ; however, it may be well worthwhile to take samples of them into a laboratory for sustained evaluation in less hostile environments. Some possible findings here may include the change of electrical properties of shale for example, when exposed to the atmosphere. It may be possible to relate microwave response to strength of the material. The magnitude of changes in the dielectric constant as a function of moisture content, and atmospheric exposure is of importance.

7.4 In situ mine measurements effort. The study of the electrical characteristics of materials in a mine must continue. Additional measurements need to be made in operational mines to acquire data to establish feasibility of measuring floor material thicknesses when the floor is either wet or dry, for probing the front face to locate discontinuities in the undisturbed coal seam, and to measure distances from a reference point to the roof, to the floor, and to the front face.

7.5 Modeling effort. Some mathematical modeling was done the last two years to predict responses and in some cases, to verify some of the experimental data. Mathematical modeling efforts should be continued. In addition, some experimental modeling should be done to determine what effects the presence of a metallic miner might have on the performance of the radar system.

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Jocelyn Spencer provided the drafting service, and Sharon Foote provided the typing service.

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APPENDIX

ABBREVIATIONS AND SYMBOLS

E_1, E_2, E_3	Electric Intensities in paths 1, 2, and 3, V/m.
R	Distance from the antennas to the coal surface, m.
c	Velocity of propagation in free space, m/sec.
d	Coal layer thickness, measured with the FM-CW system, m.
e_1, e_2	Instantaneous electric intensity in paths 1 and 2, V/m.
e_r	Instantaneous electric intensity out of the receiver antenna, V/m.
f_0	Frequency of the signal out of the mixer, Hz.
Δf_0	Difference between two signal frequencies out of the mixer, Hz.
t	Time, sec.
α	Attenuation constant, neper/m.
Γ_1, Γ_2	Reflection coefficients.
γ	Complex propagation constant.
ε	Relative dielectric constant.
ω	Angular velocity, radian/sec.
$\omega_{(t)}$	Instantaneous angular velocity of the microwave signal out of the generator, radian/sec.

Table I. Laboratory Sample Data.

Sample Number	Physical Dimensions: Surface (cm)	Physical Dimensions: Thickness (cm) Coal	Physical Dimensions: Thickness (cm) Shale	Dielectric Constant Coal	Dielectric Constant Shale	Layer Thickness From FM-CW Measurements (cm) Coal	Layer Thickness From FM-CW Measurements (cm) Shale
1	63.5 x 137	12.7	12.7	4.8 (6.3%)**	51.8 (16.3%)	12.6	
2	33 x 107	30.5	10.2	4.8*	24.7*	30.7	
3	33 x 107	19.1	11.4	9.0 (2.8%)	36.4 (1.8%)	--	
4	33 x 107	--	20.3	--	12.7 (3.9%)	--	16.6

*No moisture analysis done.

**Values in parentheses are moisture content.

Table II. Bruceton Mine.

Test Area	Physical Thickness of Layer	Measured Dielectric Constant
1	17.8 cm	6.4
2*	27.9 cm	5.6
2*	27.9 cm	6.3
3	40.6 cm	5.6

*Different points in that test area.

Table III. Bruceton Mine.

Test Area	Measured Dielectric Constant	Coal Layer Thickness From FM-CW Measurement (cm)
1 and 2	5.5	19.2 28.1
2 and 3	5.8	27.4 40.1

Table IV. Loveridge Mine.

Station	Measured Dielectric Constant
-5	7.6
0	5.3
5	4.9
10	5.2
15	4.6
20	4.2
25	3.2
30	2.5
35	3.7
40	*
45	4.5
50	6.8

*4.9 on the first test day (before water spray)
6.8 the second test day (after water spray)

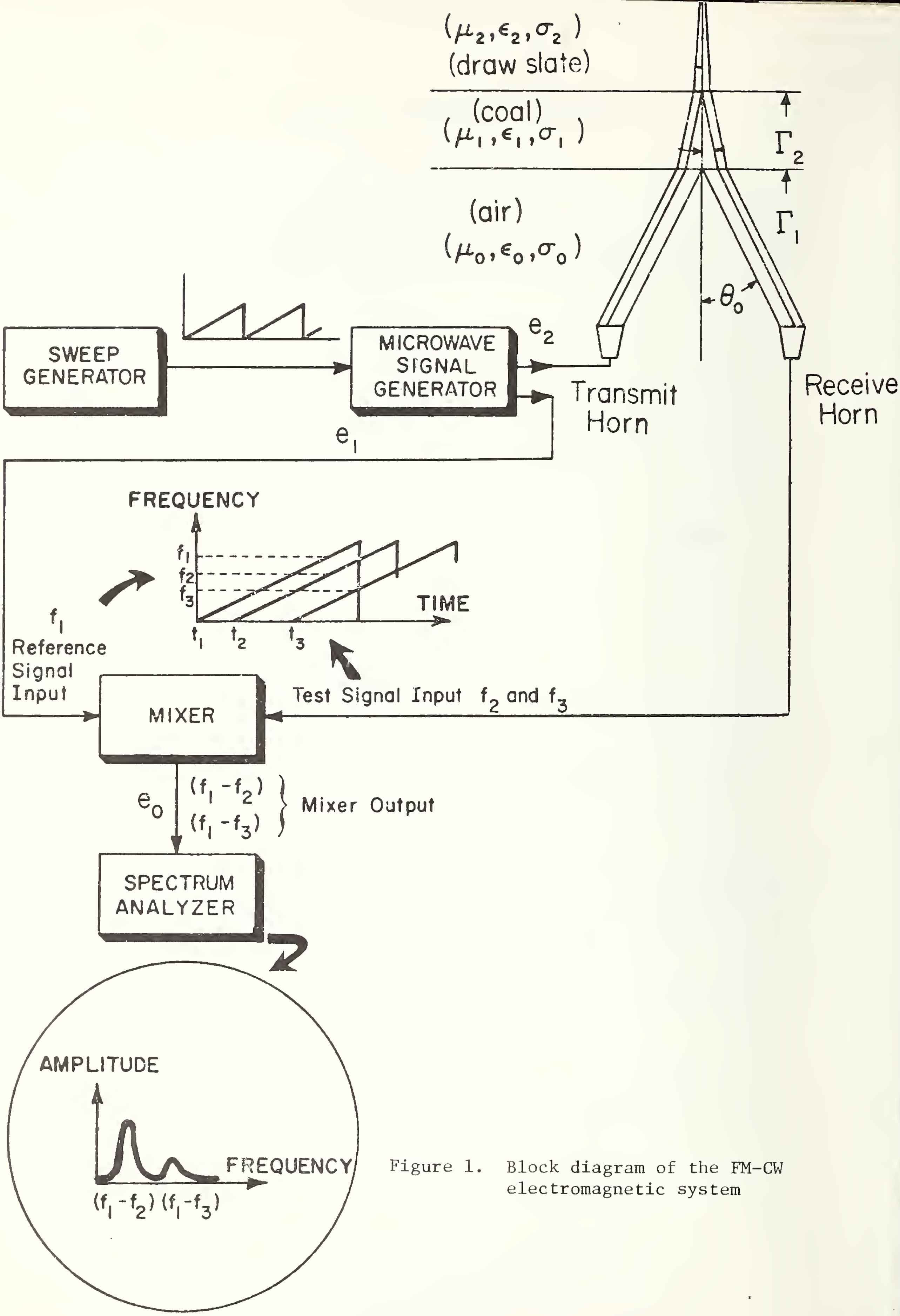
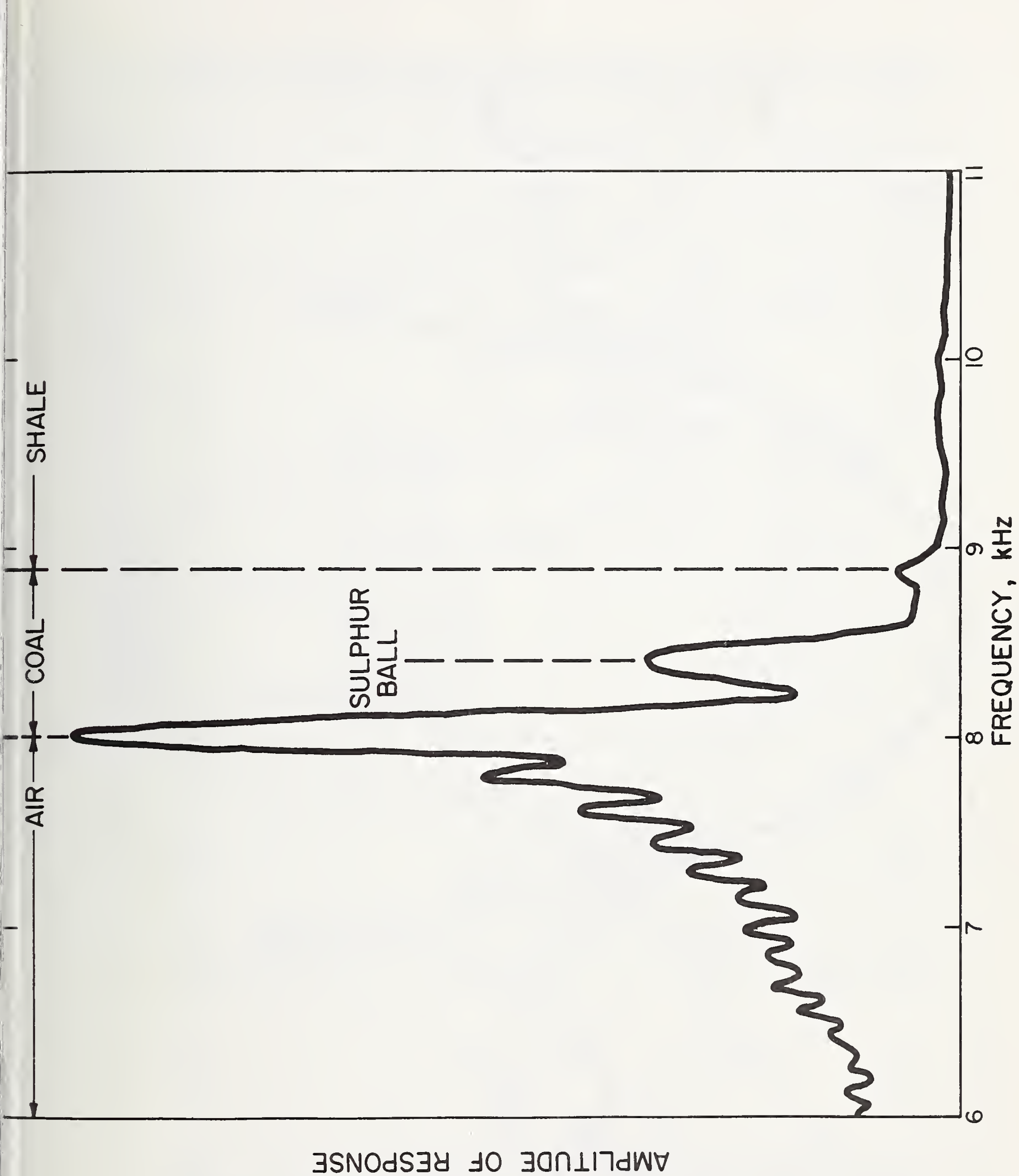


Figure 1. Block diagram of the FM-CW electromagnetic system



AIR
COAL
SHALE
SULPHUR BALL
AMPLITUDE OF RESPONSE
6
7
8
9
10
11
FREQUENCY, kHz

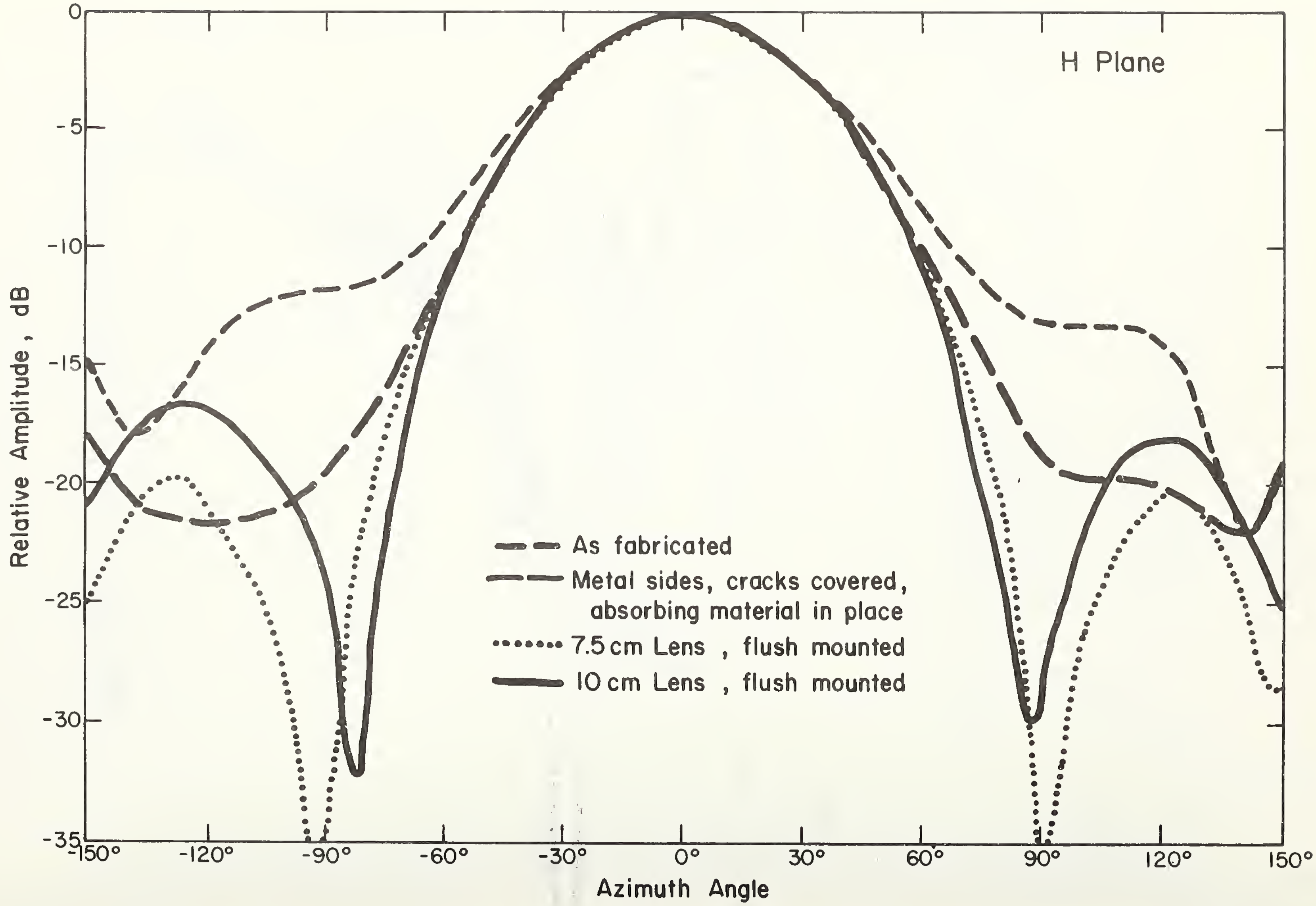


Figure 3. H-Plane field strength pattern

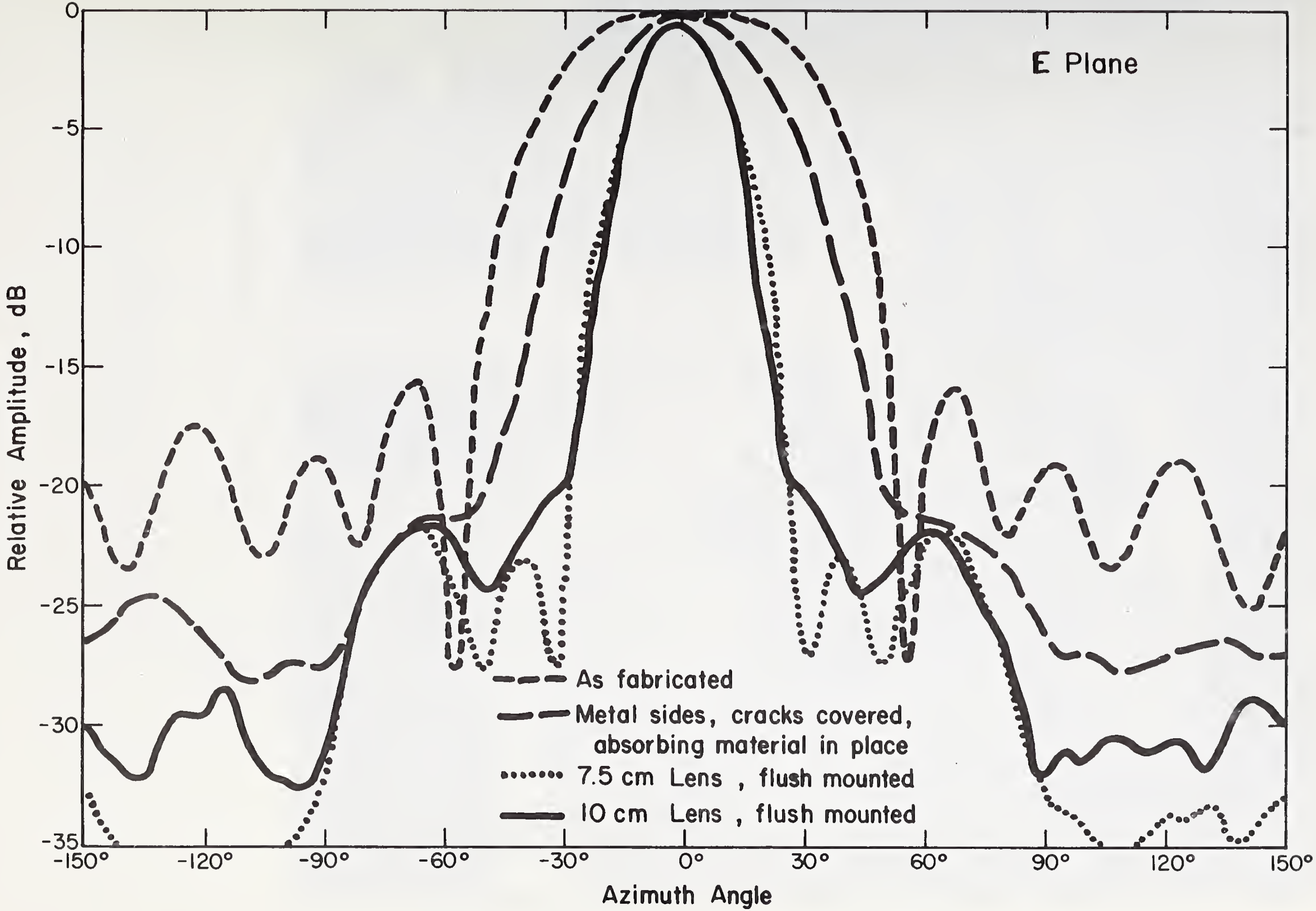


Figure 4. E-Plane field strength pattern

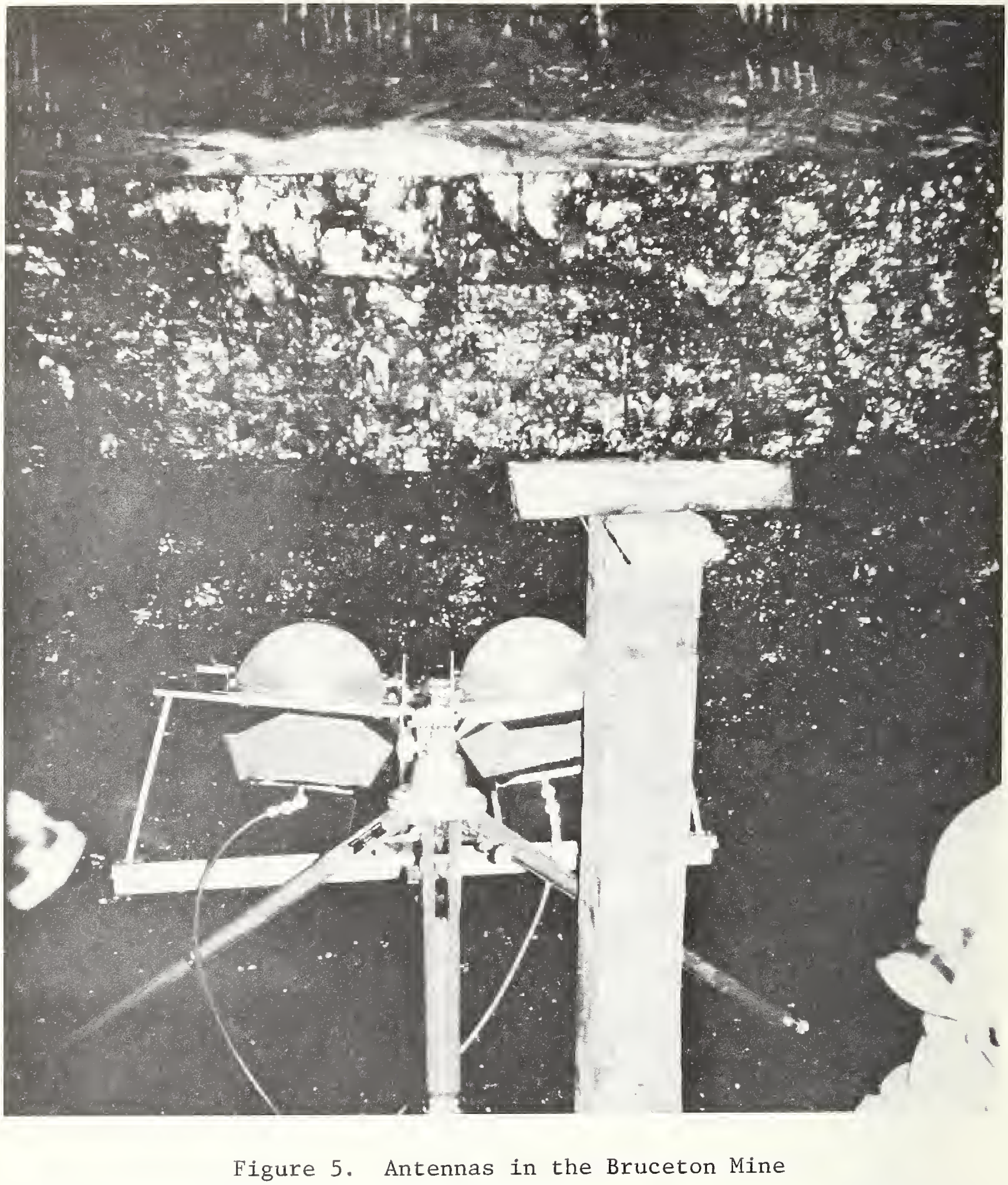


Figure 5. Antennas in the Bruceton Mine

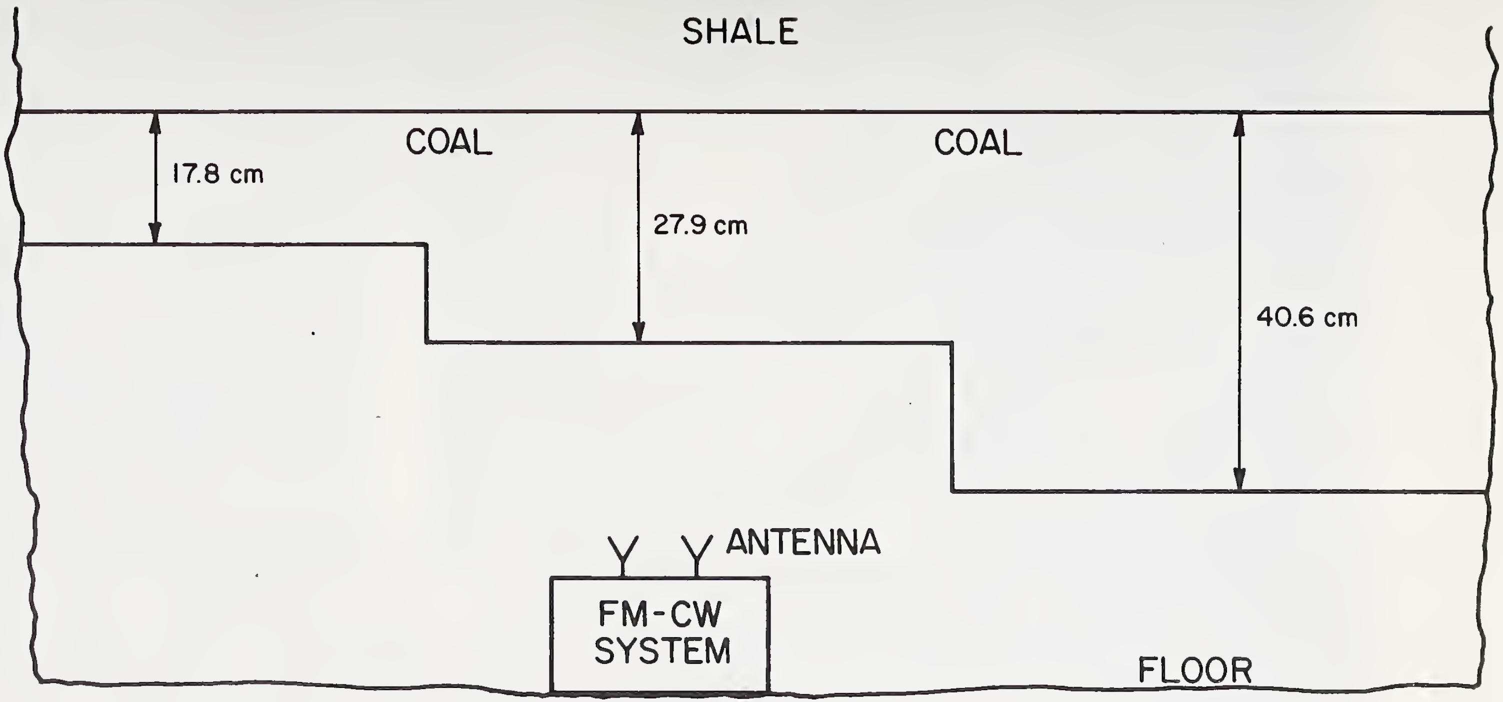


Figure 6. Test areas in the Bruceton Mine

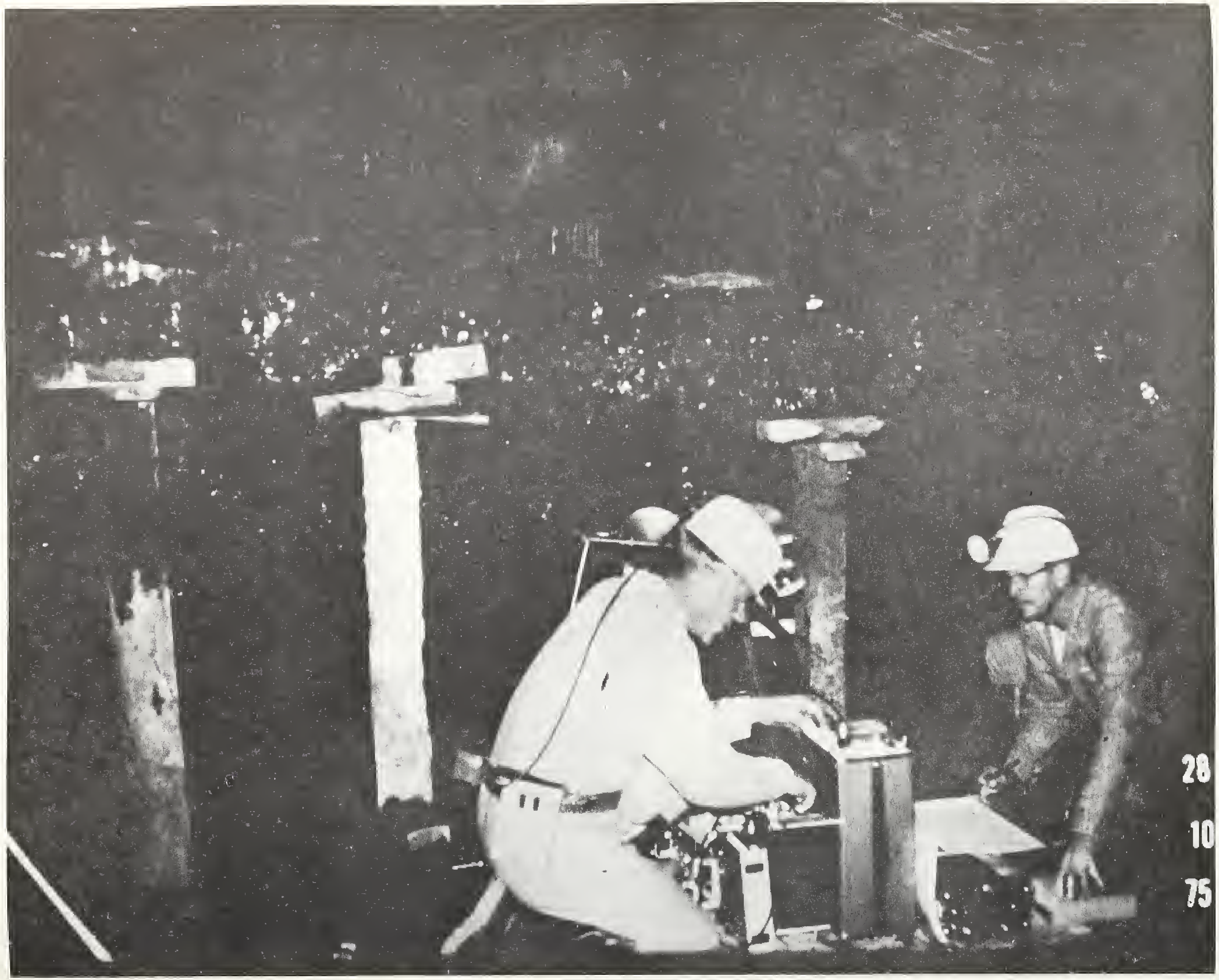


Figure 7. Measurement setup in the Bruceton Mine

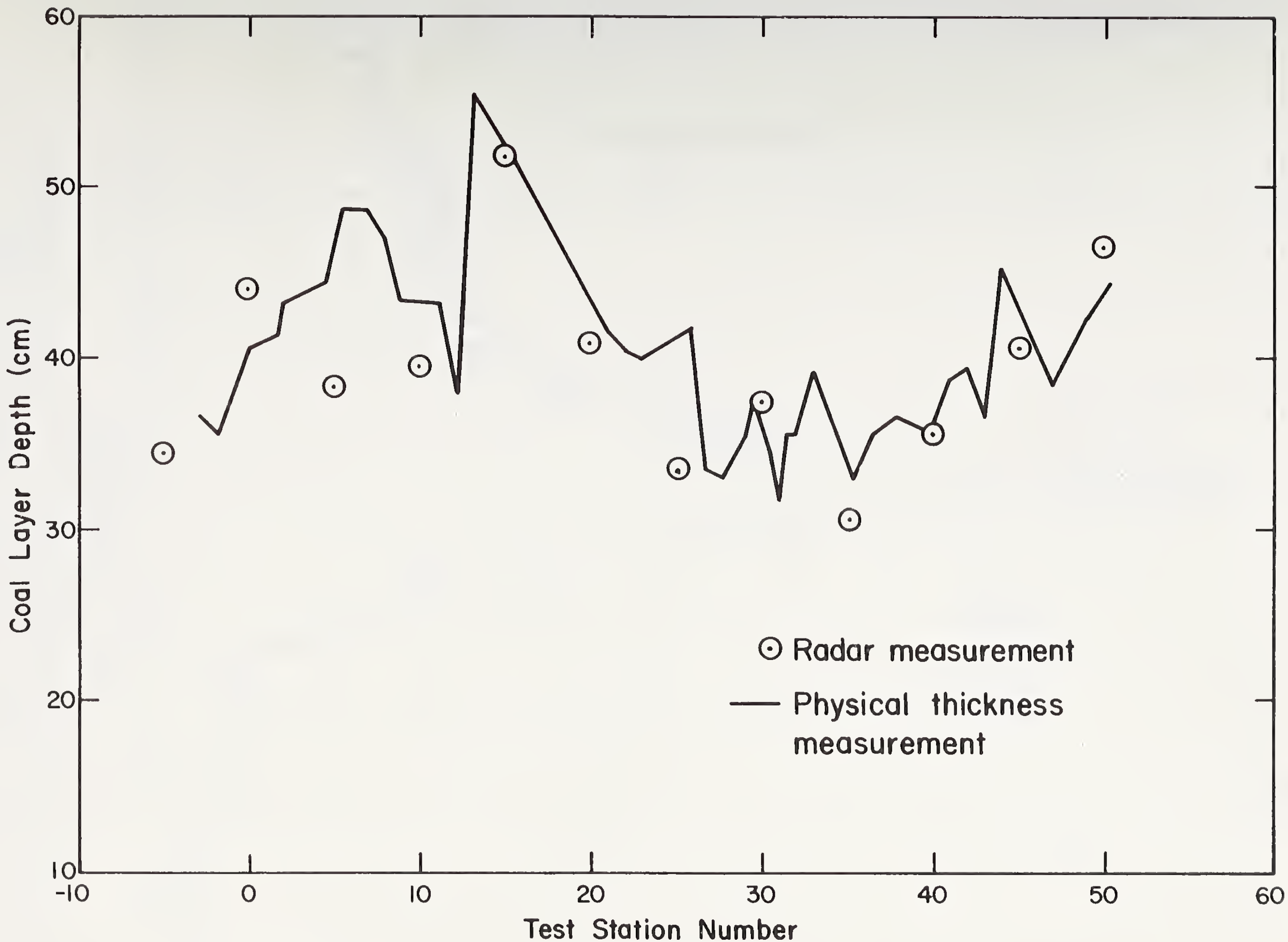


Figure 8. Coal layer depths in the Loveridge Mine

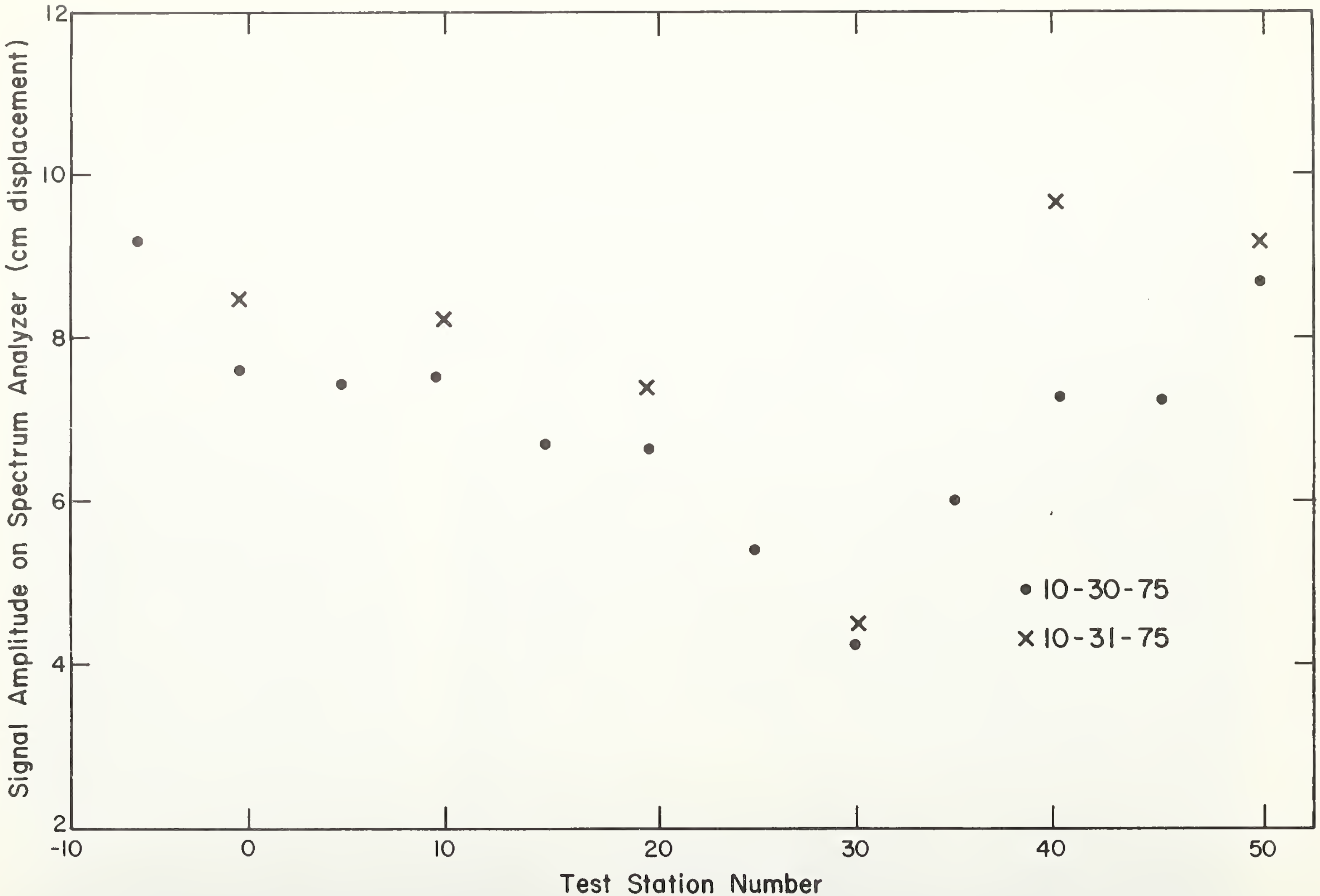


Figure 9. Relative amplitude of coal surface response in the Loveridge Mine

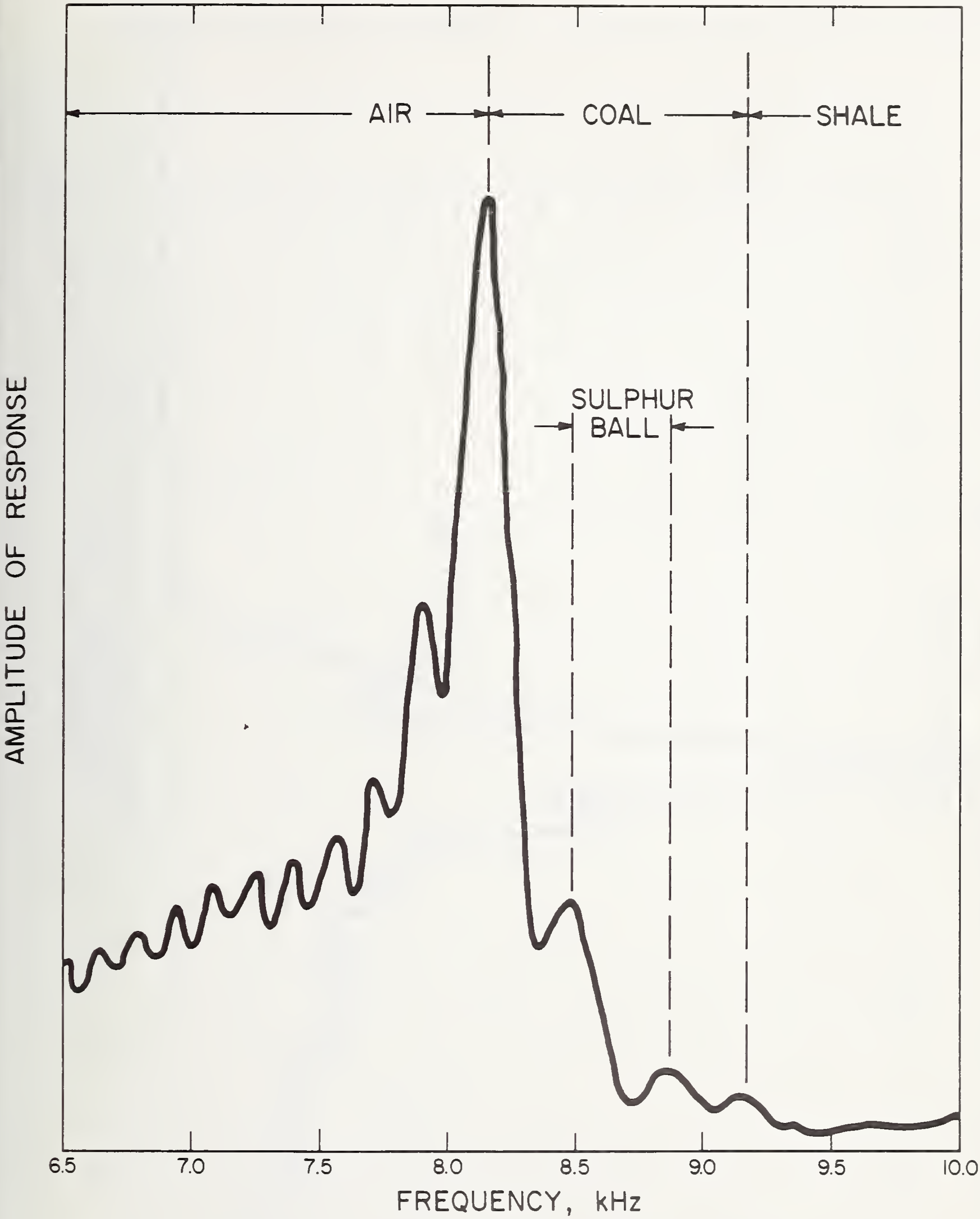


Figure 10. Raw FM-CW data from station 10 in the Loveridge Mine

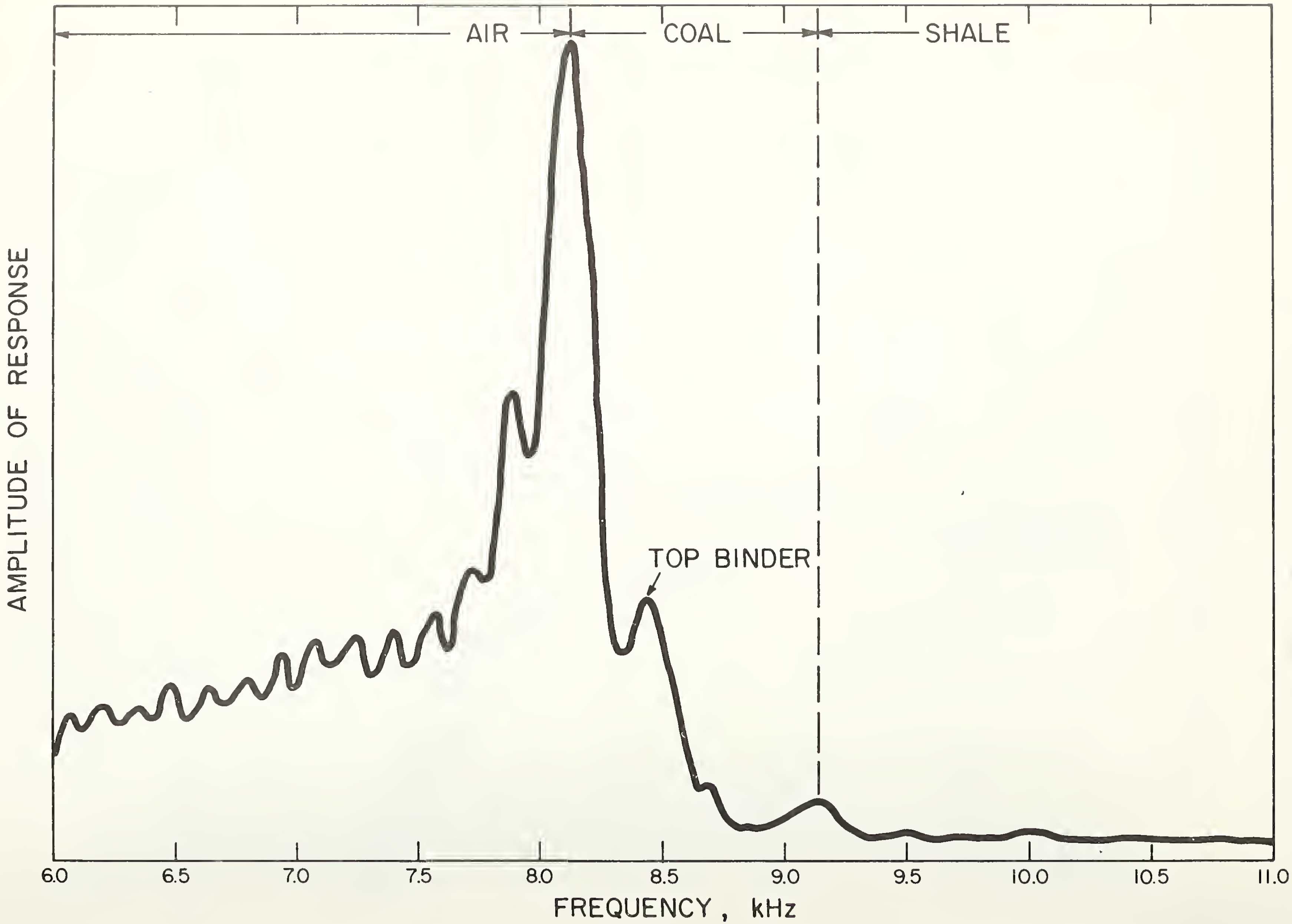


Figure 11. Raw FM-CW data taken at Station 15 in the Loveridge Mine

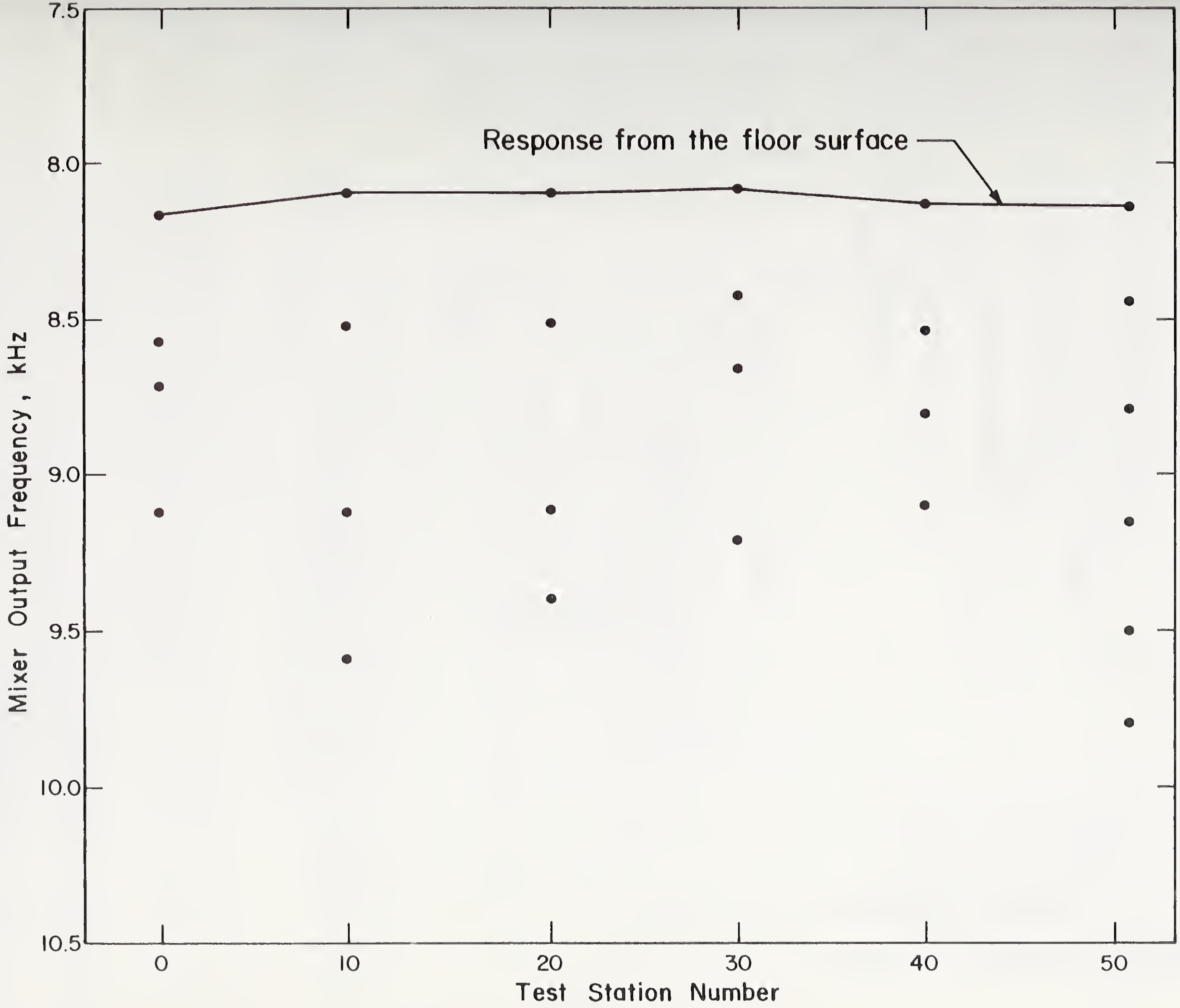


Figure 12. FM-CW floor response data in the Loveridge Mine

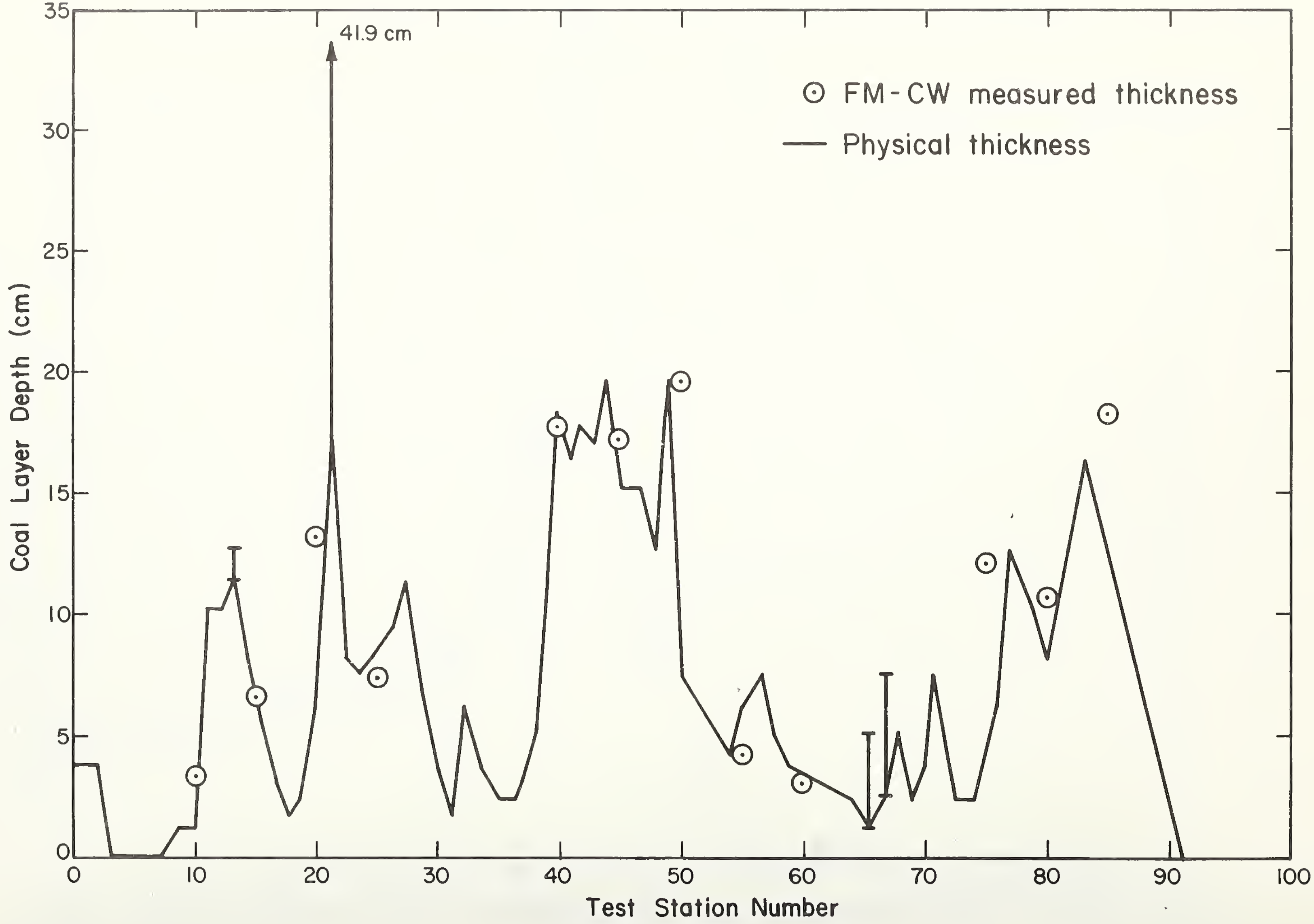


Figure 13. Coal layer depths in the Hillsboro Mine

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15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

An FM-CW microwave system was investigated for measuring coal layer thickness. Measurements were made in three different mines near Pittsburgh, Pa., near Fairview, W. Va., and near Coffeen, Ill. Microwave frequencies in the range 1-2 GHz were used to measure samples up to 55 cm thick. All samples were backed with a naturally occurring shale. Measurements were also made on coal and shale samples compounded in the laboratory at the Bureau of Mines Pittsburgh Mining and Safety Research Center near Bruceton, Pa.

The results indicate that layer thickness can be determined in most cases, although large anomalies may, in some cases, produce misleading results. Many anomalies that were detected with the FM-CW system were verified visually by drilling into the coal layer.

The dielectric constant of coal apparently varies significantly within a coal seam.

The form of the output signals from the FM-CW system seem to simplify the data interpretation and analysis process as compared to the manually swept microwave system used previously. It appears that this technique has the potential of measuring changes in the dielectric constant of a coal seam and providing an output that can be used for real-time corrections in layer thickness measurement.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)

Automation; coal; coal mine safety; dielectric constant; energy; microwave measurement; nondestructive testing; thickness of coal layer.

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