RI 8231

Bureau of Mines Report of Investigations/1977

Directionally Controlled Drilling To Horizontally Intercept Selected Strata, Upper Freeport Coalbed, Greene County, Pa.

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8231

Directionally Controlled Drilling To Horizontally Intercept Selected Strata, Upper Freeport Coalbed, Greene County, Pa.

By William P. Diamond, David C. Oyler, and Herbert H. Fields

March 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES

This publication has been cataloged as follows:

Diamond, William P

Directionally controlled drilling to horizontally intercept selected strata, Upper Freeport coalbed, Greene County, Pa. / by William P. Diamond, David C. Oyler, and Herbert H. Fields. [Washington] : Bureau of Mines, 1977.

21 p. : ill., map, diagrams ; 26 cm. (Report of investigations • Bureau of Mines ; 8231)

Bibliography: p. 21.

1. Boring. 2. Mine gases. 3. Mine ventilation. 4. Coal mines and mining. I. Oyler, David C., joint author. II. Fields, Herbert H., joint author. III. United States. Bureau of Mines. IV. Title. V. Series: United States. Bureau of Mines. Report of investigations • Bureau of Mines ; 8231.

TN23.U7 no. 8231 622.06173

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DIRECTIONALLY CONTROLLED DRILLING TO HORIZONTALLY INTERCEPT SELECTED STRATA, UPPER FREEPORT COALBED, GREENE COUNTY, PA.

by

William P. Diamond,[1] David C. Oyler,[2] and Herbert H. Fields[3]

ABSTRACT

A 3-inch pilot hole was directionally drilled to intercept the Freeport coalbed horizon horizontally at Mather, Pa., as part of a Bureau of Mines degasification project. The original concept was to continue the horizontal drilling into the coalbed, after the initial intercept, with a total of three horizontal holes eventually being completed. However, the erratic thickness (0.0 to 4.3 feet) of the Freeport coalbed at Mather was not sufficient to support the horizontal drilling degasification technique, and the site was abandoned after six attempts to locate adequate continuous coal thicknesses. The drilling of coreholes in the immediate vicinity of proposed well paths to evaluate coal thickness is essential prior to future slant hole operations.

Although mechanical failures of the new directional drilling equipment, mud pump and rig breakdowns, directional control problems, and exploratory horizontal drilling in the Freeport horizon more than doubled the anticipated cost of the pilot hole, continuing improvements in directional drilling equipment and techniques should significantly reduce the time and costs of future drilling operations.

INTRODUCTION

The Bureau of Mines in its continuing research in coalbed degasification is currently evaluating directional drilling techniques for methane drainage of large areas from a single surface location. Large quantities of methane gas are expected to be drained from coalbeds using this technique. The Freeport coalbed at a site near Mather, Pa., was selected for this research drilling project since desorption of coal cores in sealed canisters indicated that over 200 cu ft of methane per ton of coal is present in the Freeport coalbed at depths of 1,000 feet.

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[3] Mining engineer.
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The Freeport coalbed has not been mined in the area of the research site, but mining operations are planned for the future. The purpose of this research was to provide information on the use of directional drilling techniques for degasification in advance of mining for both mine safety and energy resource utilization. This report details the equipment specifications, drilling technology, and cost of the slant hole to the Freeport coalbed. An evaluation of the geologic factors that necessitated the abandonment of the initial research site after reaching the Freeport coalbed horizon is included, and precautions for future site selection are given.

ACKNOWLEDGMENTS

The authors greatly appreciate the cooperation of the Jefferson-Morgan Mining Co., a division of Jones & Laughlin Steel Corp., Mather, Pa.; Dyna-Drill Co., Long Beach, Calif.; Sperry-Sun, Houston, Tex.; Paramount Exploration, Inc., Waynesburg, Pa.; and Bob Croom, Inc., Lafayette, La., for helping make this work possible. Many individuals, too numerous to mention, were especially helpful, but we acknowledge posthumously the devotion and professional concern exhibited by Ken Austin, the late president of Paramount Exploration, Inc., who for the last 5 years of his life was deeply involved in the technical aspects of producing gas from coalbeds.

DRILLING PROGRAM

General Drilling Plan

The Freeport coalbed horizon was known to be approximately 930 feet below the surface at the drill site. A drill path was calculated which, starting with a 5° tilt of the rig and 6° deviation per 100 feet of drilled depth, would intercept the coalbed horizontally. A 3-inch pilot hole was to be drilled to the Freeport coalbed and 50 feet horizontally into the coalbed with a 2-3/8-inch Dyna-Drill.[4] Standard BQ drilling rod was used with a 60-foot section of stainless steel rod just above the Dyna-Drill tool. The nonmagnetic rods are necessary for directional surveying.

The initial hole was to be reamed to a 10-inch diameter using a stinger extending 2-1/2 feet beyond the drill bit to keep the hole on course. Seven-inch casing was to be cemented in place to just above the coalbed. From the bottom of the casing, the pilot hole would be underreamed to a 10-inch diameter for a horizontal distance of 50 feet. From this large hole, at least three individual 3-inch holes were to be drilled at various angles to a depth of approximately 3,500 feet into the coalbed.

Equipment and Site Layout

A hydraulically operated Reed Exploratory rotary drill was used on this hole. The drilling assembly was mounted on an International Harvester model F2010A truck with a 208-inch wheelbase. The mast height was 45 feet

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[4] Reference to specific equipment, trade names, or manufacturers does not imply endorsement by the Bureau of Mines

with the hydraulic cylinders retracted and 79 feet when fully extended. The rear-end loader was capable of handling 30-foot lengths of drill pipe. Hoist capacity was 70,000 pounds, and pulldown capacity was 26,000 pounds. Power was provided by a Cummins NT855-P380 diesel engine developing 380 bhp at 2,100 rpm. A Grimmer Schmidt 903-82 air compressor rated at 660 cfm at 100 psi and 575 cfm at 210 psi also was mounted on the rig.

The hole was drilled with Baroid's Dextrid colloidal, organic, polymer mud. The Dextrid additive produces a mud with a very low filtration rate, from 6 to 13 ml per 30 min, averaging about 8 ml per 30 min, which aids in shale stabilization. A red shale section approximately 300 feet above the Freeport coalbed is particularly troublesome, causing frequent drilling

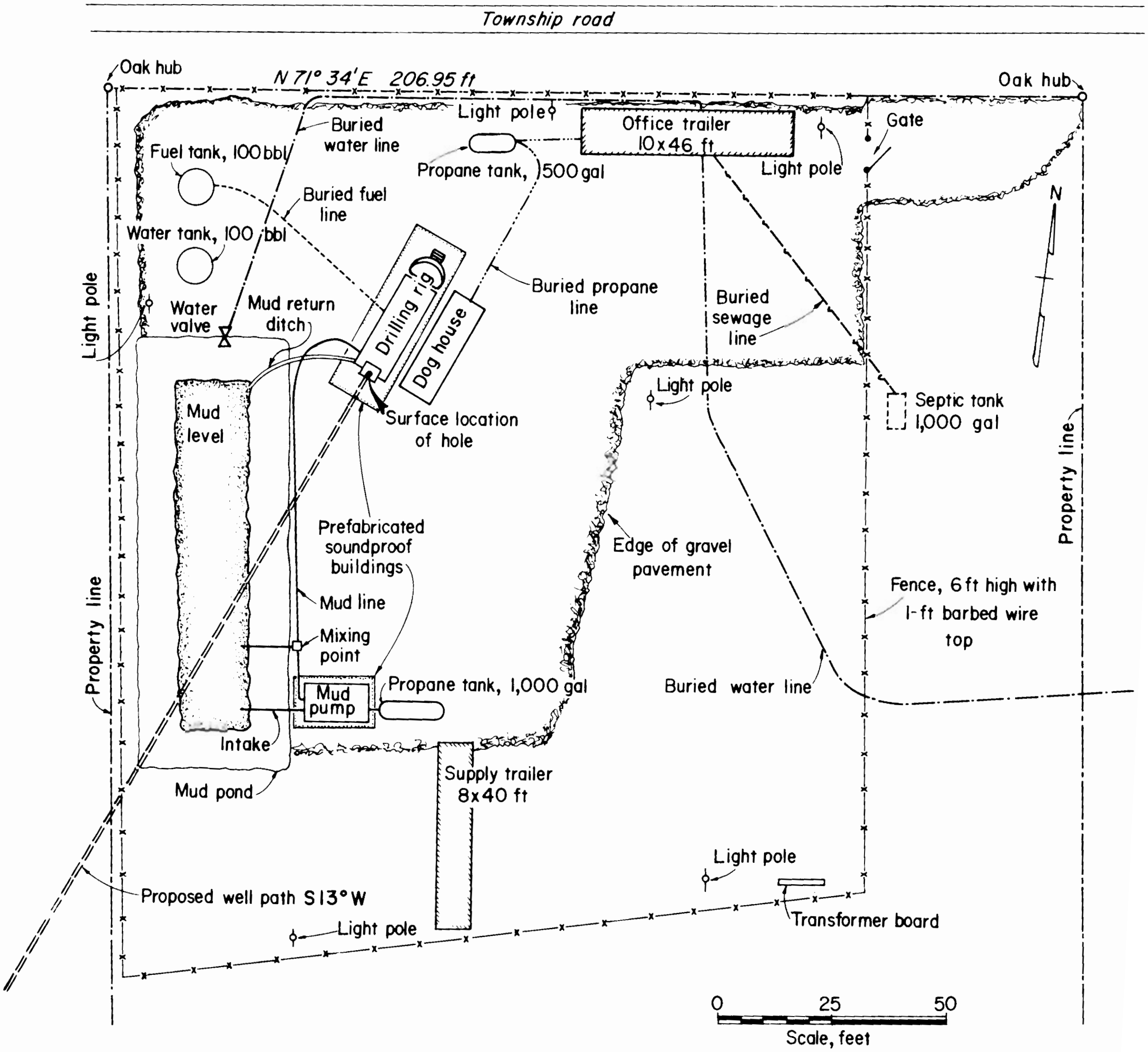

FIGURE 1. - Plan view of equipment layout at drill site.

problems due to swelling and sloughing of the shale. Mud weights typically ranged between 8.3 and 8.4 lb/gal. The funnel viscosity (1,000 cu cm) ranged from 30 to 33 sec. No hole problems were encountered with the mud system used during the 4-1/2 months of drilling operations.

The fenced-in drill site is approximately 165 feet wide and 180 feet deep for a total area of about 30,000 sq ft. Figure 1 shows the placement of the drill rig, mud pit and pump, supply and office trailers, and other equipment necessary for the drilling operation. The drilling area was surrounded by a 6-foot-high, chain-link fence as a safety precaution since the site is near a residential area. Adequate lighting was provided for night drilling operations. The drill rig and mud pump were enclosed with plywood buildings to reduce noise levels during drilling.

GEOLOGIC FACTORS CONTROLLING DIRECTION OF DRILLING

The direction of drilling for the slant hole and subsequent horizontal holes was dependent upon geologic factors. The Freeport coalbed does not maintain a constant thickness in the area of the drill site, varying from no coal to nearly 8 feet. It is desirable to drill the horizontal holes in the thickest and least variable parts of the coalbed. This will aid in keeping the advancing horizontal holes in the coalbed and out of the surrounding strata. Also, the greatest amount of coal will be subject to degasification in the thicker parts of the coalbed.

Before the start of the drilling project, corehole data in the immediate vicinity of the drill site indicated that the freeport coalbed thins in the northwest, northeast, and southeast quadrants, and is thickest in the southwest quadrant. The area of the thickest coal (greater than 5 feet) was presumed to be located between S 4° W and S 85° W, with the surface location as the origin.

A critical factor for maximum gas flow from coalbeds is the cleat system. Degasification experiments conducted underground in coal mines (5)[5] have shown that horizontal holes drilled perpendicular to--and therefore intersecting the largest number of--face cleats will yield 2.5 to 10 times more gas than holes drilled perpendicular to the butt cleat. The underground mine nearest to the drill site is the Gateway mine, operating in the Pittsburgh coalbed, approximately 600 feet above the Freeport. The face cleat measured in this mine strikes at N 68° W (7). Recent investigations by the Bureau of Mines (8) indicate that cleat systems maintain similar orientation throughout a vertical section at one location. Therefore, it was assumed that the face cleat in the Freeport coalbed would be near N 68° W. Taking into account the thickest coal in the southwest, and the desirability of penetrating the coalbed as nearly perpendicular to the face cleat as possible, the initial hole was drilled S 13° W.

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[5] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

Two important factors in selecting a surface location for the hole were the presence of abandoned mine workings in the Pittsburgh coalbed beneath the site and environmental considerations. Figure 2 is a map of the drilling location with the underground passageways and coal pillars superimposed. It was essential to drill through a solid block of coal and not through a mined-out area. Encountering a mined-out area would have resulted in a loss of expensive drilling fluids and would have necessitated cementing to fill the void, reaming a larger hole, and setting a string of casing through the coalbed, or else redrilling the hole from a different surface location. Either alternative would entail lost time and added expense.

The southern portion of the location is heavily wooded and bounded by an 80-foot cliff into Tenmile Creek. To minimize the effect of drilling operations on the environment, the surface location was placed on the unforested, northern portion of the site. The horizontal displacement of the proposed well path at the anticipated depth of the Pittsburgh coalbed was calculated to

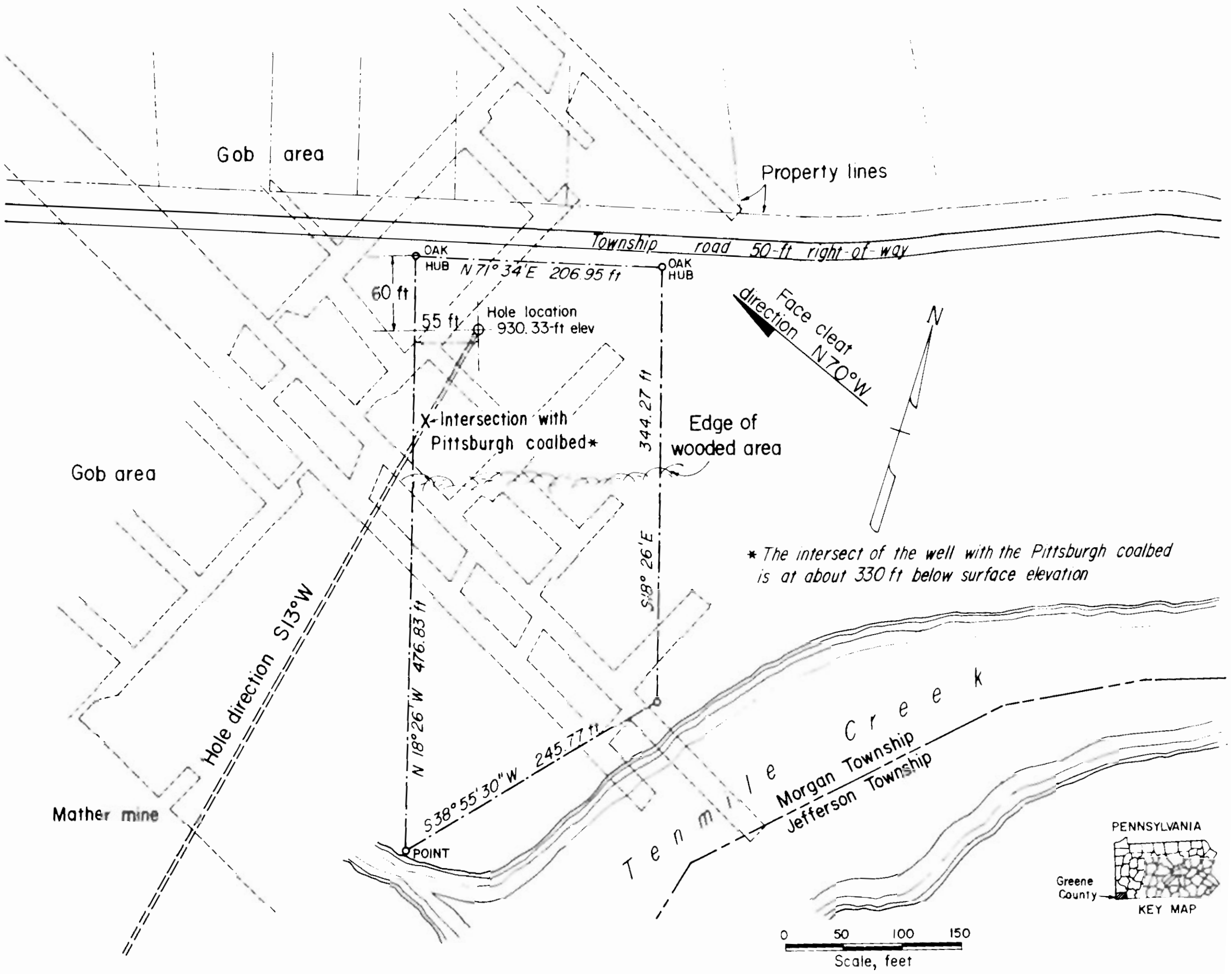
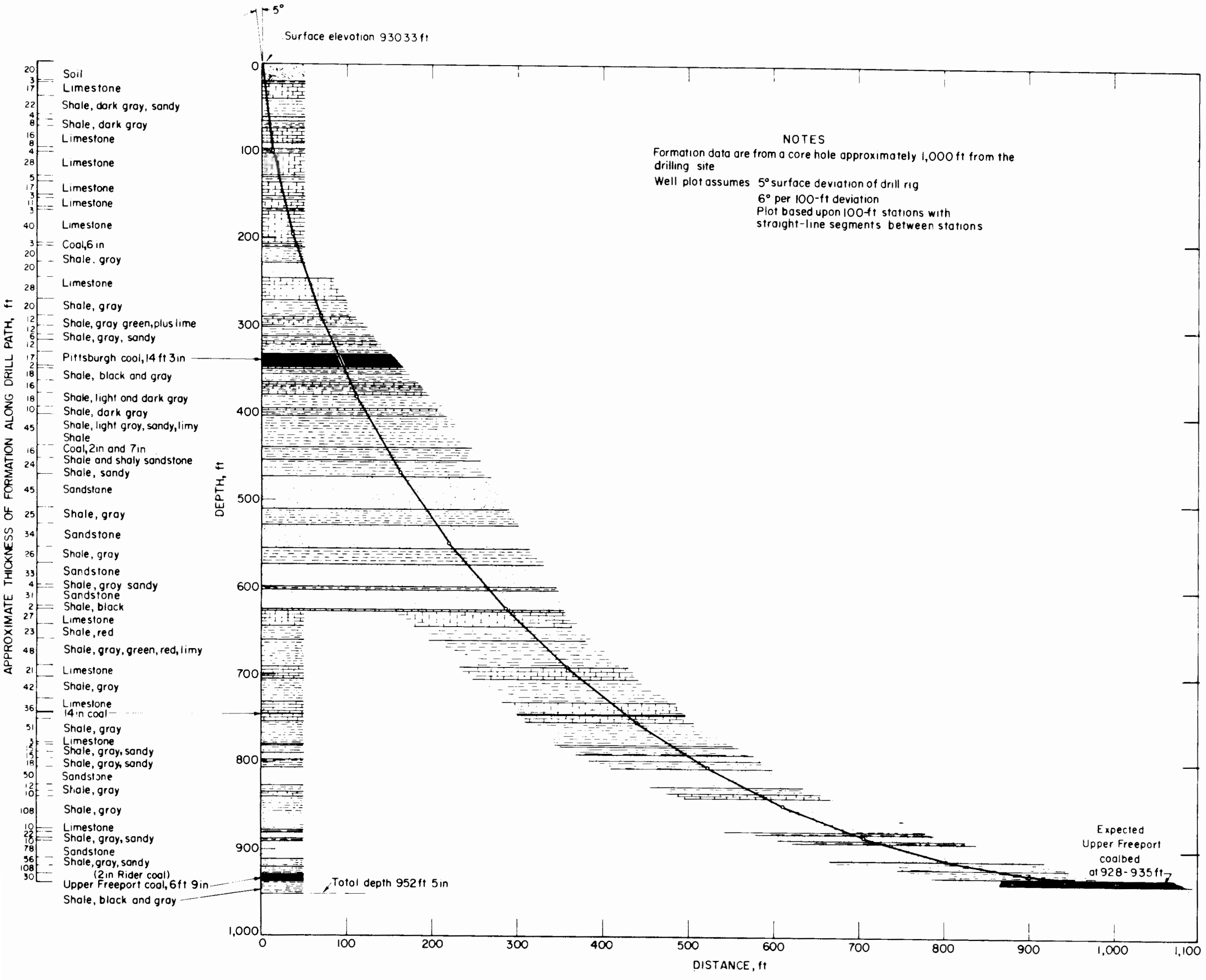


FIGURE 2. - Plan view of drill site and underground workings in the Pittsburgh coalbed.



NOTES

Formation data are from a core hole approximately 1,000 ft from the drilling site

Well plot assumes 5° surface deviation of drill rig
6° per 100-ft deviation
Plot based upon 100-ft stations with straight-line segments between stations

FIGURE 3. - Section view of proposed slant hole well path with geologic column.

be approximately 90 feet (fig. 3). The center of the large block of coal, approximately 140 feet south of the northwest corner of the location, was chosen as the target in the Pittsburgh horizon. The prime surface location then was determined to be along N 13° E to S 13° W from the center of the block of coal and at a horizontal distance of 90 feet (fig. 2). The pilot hole was drilled with slightly less deviation than expected in the top section, but the block of coal was encountered at a vertical depth of 333 feet (597 feet above sea level) and 70 feet from the surface location (fig. 4).

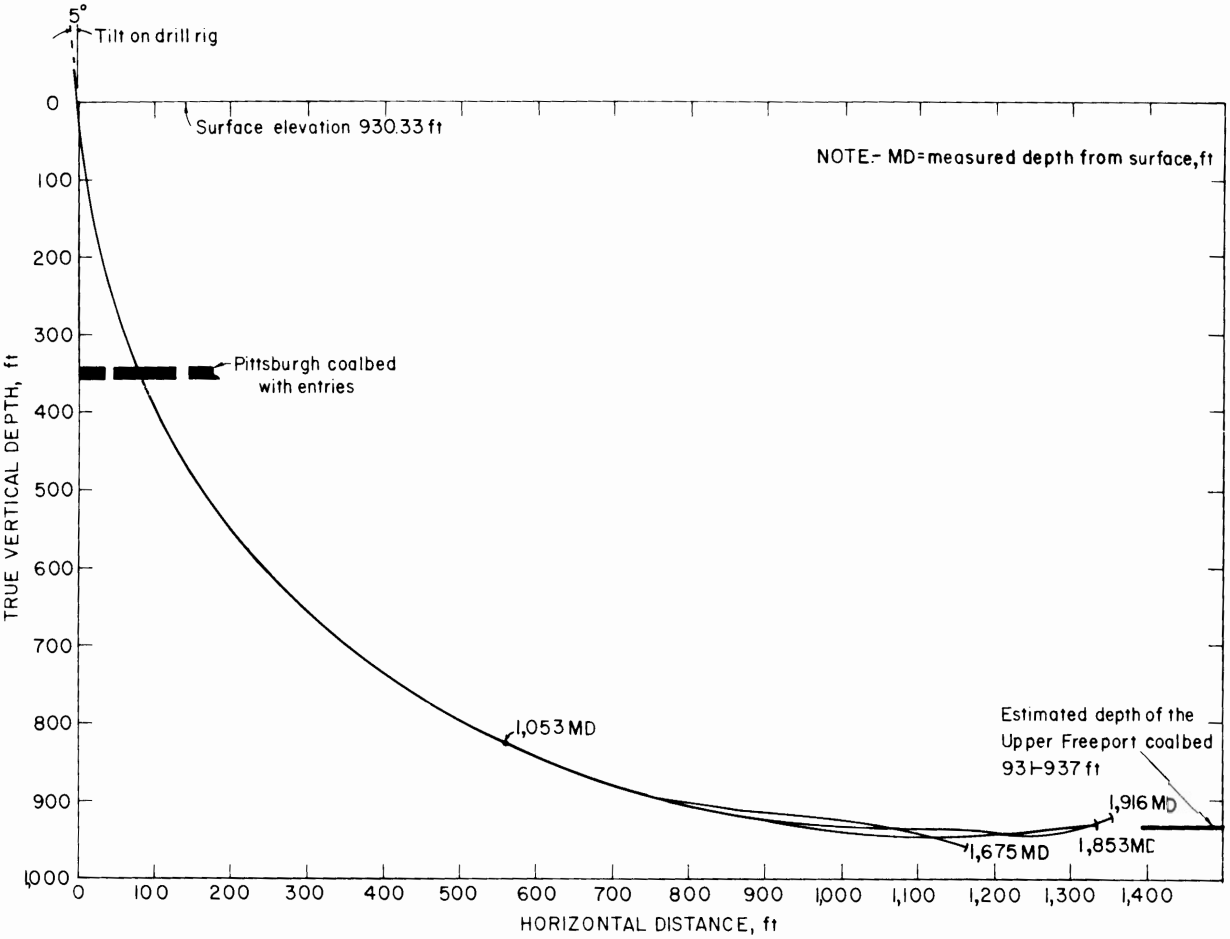


FIGURE 4. - Section view of actual well path drilled.

DESCRIPTION OF DYNA-DRILL

To drill a hole from a near vertical position at the surface and intercept a coalbed horizontally nearly 1,000 feet below requires the use of special drilling techniques. To achieve directional control, a Dyna-Drill was selected. The Dyna-Drill tool (fig. 5) is essentially a positive displacement mud motor encased in a housing and attached to a drill bit. The drill bit is driven by the downhole motor without drill pipe rotation. Because the drill pipe does not turn, it is possible to orient the drill pipe and the attached Dyna-Drill tool to control the direction of penetration.

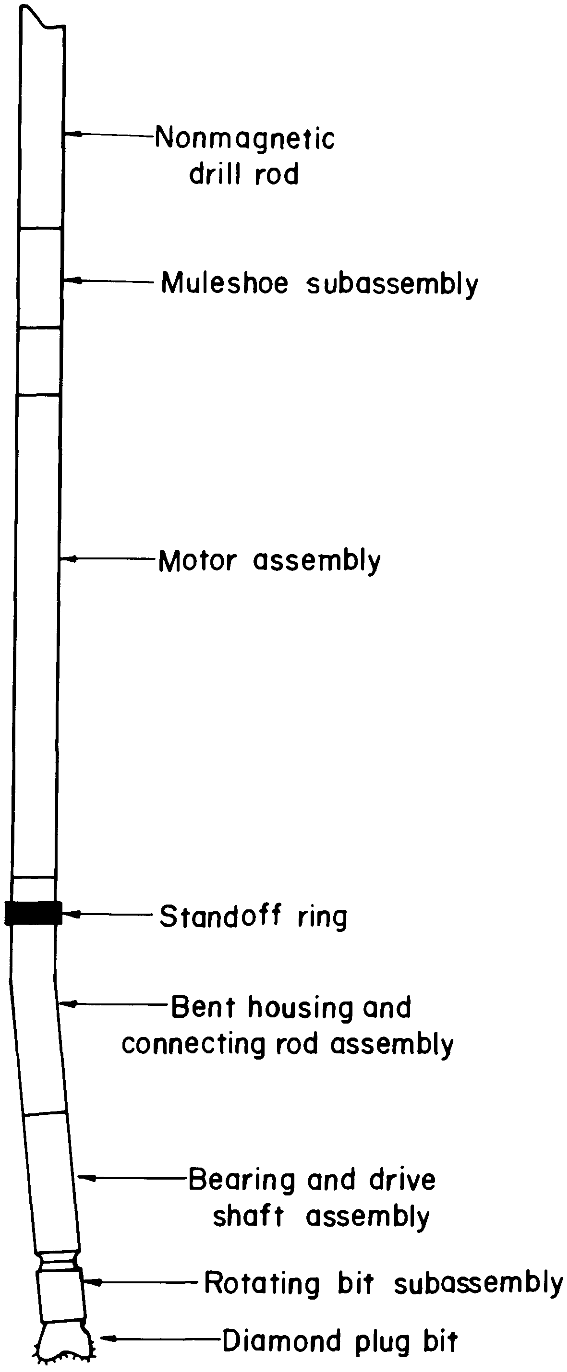


FIGURE 5. - Dyna-Drill tool assembly.

A 2-3/8-inch Dyna-Drill with a 3-inch Christensen NX diamond plug bit, style D-41, was used during routine drilling of the pilot hole. A specially designed diamond sidetracking bit was used when sidetracking was necessary. A mud pump pressure of 400 to 600 psi was normally required to start the mud pump motor in the Dyna-Drill tool when on the bottom. Occasionally, pressures as high as 1,000 psi were required for new assemblies. A 300-psi mud pressure differential over the off-bottom operating pressure at 25-gpm flow rate is ideal for maximum control and penetration.

Larger Dyna-Drill tools are available which would eliminate reaming the pilot hole. A larger Dyna-Drill was not used because of the greater difficulty in controlling angle of deviation, which is very critical in the drill path needed to intercept the coalbed horizontally. The rental cost of the larger Dyna-Drill also is much higher, making it prohibitively expensive for projects of long duration.

Several subassemblies on the Dyna-Drill tool must periodically be changed because of wear which could cause malfunctions. The bearing and U-joint packages must be changed after about 100 hours of use. Improvement of these assemblies may extend their inhole operating time. The motor assembly normally can run 500 to 600 hours or more, depending on how free of extraneous matter the drilling fluid is. There was no indication of wear on the motors used on this project. This probably was due to the low solids content and general high quality of the drilling mud used.

DIRECTIONAL CONTROL USING THE DYNA-DRILL

The amount of deviation achieved by the Dyna-Drill can be varied by using either interchangeable bent subs or housings of various angles. Bent housings of 30 and 45 minutes were used on this hole. The higher the sub or housing angle, the greater the amount of deviation. A standoff ring also can be incorporated as part of the tool above the bent assemblies to hold the tool slightly off the bottom on the low side and thereby increase the penetration angle. The deviation was primarily controlled by varying the bit pressure: The higher the bit pressure, the greater the amount of deviation. The changes in bit weight were read at the surface as changes in mud pressure. Using bit weights to control angle also affected penetration rates. In formations such as shale, where a tendency to build angle at too great a rate was experienced, lowering the bit pressures produced a decrease in penetration rate. Penetration rates in sandstone and limestone were not affected as severely by changes in bit pressure.

Azimuth control of the pilot hole was not as critical as the angle of inclination, but for side tracking and drilling multiple horizontal holes in a coalbed from the bottom of a single slant hole, it did become important. Control of azimuth was obtained by turning the bend in the bent housing to the left or right. This technique of azimuth control was also tried as a method to slow the rate of increase of inclination, but was found to be of little value.

SPERRY-SUN SINGLE-SHOT SURVEYING TECHNIQUES

To determine the exact position of the advancing slant hole, Sperry-Sun single-shot surveys were made every 10 feet of measured depth. These surveys provided data to calculate the direction of penetration, the true vertical depth, and the coordinates of the survey point. These data, in conjunction with the proposed drill path plot (fig. 3), were used to determine what Dyna-Drill subassemblies, mud pressures, and tool orientation were used to maintain the proper well path.

The single-shot survey system consisted of a wire line instrument package and a drill pipe subassembly (mule-shoe sub) attached just above the Dyna-Drill tool. The instrument package was lowered to the bottom of the hole through the drilling rod. Inside the instrument package were a directional compass and a lens and lamp system, which made a permanent photographic record of the true magnetic directions and the inclination of the hole. The actual survey point was above the bottom of the hole since the Dyna-Drill tool was about 9 feet long and the survey tool fit into the mule-shoe sub directly above the Dyna-Drill. To remove the extraneous magnetic effect of regular drill rods, it is necessary to use stainless steel or aluminum pipe. Sixty feet of stainless steel BQ rod was used above the mule-shoe sub.

The lens system which produced the photographic record was set off by a hand-wound, mechanical clock. The clock can be set with a delay of up to 1 hour. Clocks with 30-minute and 2-hour delays also are available. Normally a 10-minute delay is sufficient to lower the survey instrument to the bottom. As the angle of the hole reached about 55° to 65°, it became necessary to pump the survey tool to the bottom of the hole due to the friction against the inside of the drill rod. A pump-down stuffing box was attached to the top of the drill rod for this procedure. This assembly has a connection for the mud line and a small hole in the top through which the wire line of the survey tool passes.

CALCULATION OF SINGLE-SHOT SURVEYS, DOGLEG SEVERITY, AND WELL PROJECTIONS

Single-Shot Survey Calculation

The single-shot surveying tool gives a reading of the well position in terms of an inclination angle θ_I, a bearing angle θ_B, and a drilled length ΔL (fig. 6). These values are trigonometrically broken up into two sets of components: ΔLat and ΔDEP; ΔTVD and ΔVS. The sum of these values from all previous surveys of the hole gives the new hole position. The latitude and departure then give the bottom-hole position in a plan view, and the vertical section and true vertical depth give position in a cross section along the projected path of the well. The equations for calculating components are given with their definitions in table 1.

The tangential method was used on this project for calculation of the single-shot surveys. More complex methods may be used to calculate hole

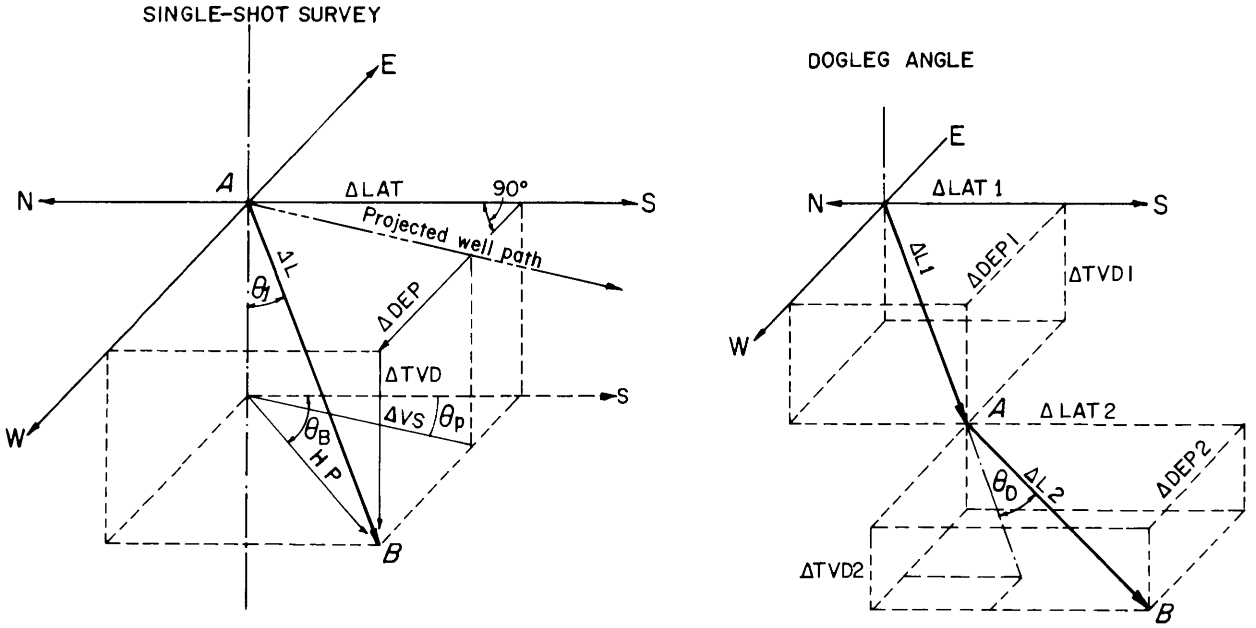


FIGURE 6. - Geometry of single-shot survey and dogleg angle calculations.

position. For instance, the drilled distance may be more accurately approximated as the arc of a circle. At short surveying intervals as used here, the inaccuracy caused by using the sum of a large number of triangles becomes negligible.

TABLE 1. - Definitions of terms used in single-shot survey and dogleg severity calculations

Term	Definition
θ_P	Projected well azimuth planned for the well. Given in degrees E or W of N or S.
θ_B	Azimuth actually drilled along. Obtained from the single-shot reading. Given in degrees E or W of N or S.
θ_I	Inclination of the hole with the vertical. Obtained from the single-shot survey. Given in degrees.
ΔL	Length drilled between surveys. Given in feet.
Vertical section	Horizontal distance drilled parallel to the projected well path. Bearing of this line is θ_P.
Latitude	Total distance drilled N or S of the surface location.
Departure	Total distance drilled E or W of the surface location.
True vertical depth	Total vertical distance drilled from the surface.
HP	Projection on the horizontal of the drilled distance. $HP = \Delta L \cdot SIN\theta_I$
ΔTVD	Vertical distance drilled in ΔL feet. $\Delta TVD = \Delta L \cdot COS\theta_I$
ΔDEP	Distance drilled E or W of NS line in ΔL feet. $\Delta DEP = [\Delta L \cdot SIN\theta_I] \cdot [SIN\theta_B]$
ΔLat	Distance drilled N or S of an EW line in ΔL feet. $\Delta Lat = [\Delta L \cdot SIN\theta_I] \cdot [COS\theta_B]$
ΔVS	Vertical section distance drilled in ΔL feet. $\Delta VS = [\Delta L \cdot SIN\theta_I] \cdot [COS(\theta_B - \theta_P)]$
θ_D	Dogleg angle.

Dogleg Severity Calculation

The rate of change in angle is important because if this rate of change is too large, it may not be possible to run casing in the hole. The dogleg angle θ_D (fig. 6) is measured from both the change of inclination and the change of bearing between two points.

The following equation is used to calculate dogleg severity between two points:

$$\mathrm{Cos}\theta_D = \frac{[(\Delta TVD1)\cdot(\Delta TVD2)+(\Delta LAT1)\cdot(\Delta LAT2)+(\Delta DEP1)(\Delta DEP2)]}{(\Delta L1)\cdot(\Delta L2)} .$$

This formula gives the dogleg angle over a distance equal to $\Delta L(\Delta L=\Delta L1=\Delta L2)$ because it represents the change in angle from point A to point B (fig. 6)

The accuracy of the single-shot survey computations must be quite high. If only two-place accuracy were used, the cosine value might be greater than one. This is obviously incorrect since the cosine function varies from -1 to +1. This is one reason why it is convenient to use a small computer or calculator for these computations. It gives accurate values of θ_D with much greater ease and speed than can be obtained from either hand computation or tables. Tables of dogleg values are available, although the table known to the authors reads only to deviations of 65°.

It is important that the dogleg be kept within the maximum deflection angle of the casing to be run. Over a short interval of severe dogleg, it is possible to ream the hole to run casing despite a dogleg greater than the maximum allowable deflection. However, the necessary diameter of the reamed hole increases rapidly even with small angle differences.

Method of Choosing a Slant Hole Projection

Before the start of drilling, it is necessary to construct a projected well path from the surface to the target horizon (fig. 3). This "ideal" path is then used as a guide for the actual drilling. The most desirable well path is a circular arc from the surface to the coalbed. A well path of this geometry will minimize dogleg angles. It also allows drilling to shallower target depths than any other well path.

For a circle, the angle subtended by a particular arc is--

$$\Delta\theta/\Delta L = \frac{180}{\pi}\frac{\Delta L}{TD} ,$$

where $\Delta\theta/\Delta L$ = central angle subtended by an arc of ΔL feet,

ΔL = arc length (a drilled distance ΔL),

TD = radius of a circle (the vertical distance from the coalbed to the surface),

and $\frac{180}{\pi}$ = conversion factor--radians to degrees.

The expected vertical depth to the Freeport coalbed (TD) at Mather, Pa., was 928 feet, and the arc length (ΔL) was set for convenience at 100 feet. The equation then gave the change of inclination per 100 feet ($\Delta\theta/\Delta L$) as 6.17°. Because of possible problems in running casing in holes with large dogleg angles, $\Delta\theta/\Delta L$ was set at 6° per 100 feet to minimize the problem. This meant that the initial hole could not be started vertically at the surface and still allow the well path to reach the target. The drill rig was designed to work at angles up to 10°. Surface angles from 0° to 10° were mathematically tested to determine the proper angle of the initial hole. An angle of 5° at the surface was found to be sufficient.

The well path projections were made using the same calculations as were used for the single-shot surveys, except that ΔL was set at 100 feet, $\Delta\theta$ was set at 6°, and θ_B was set at 0°. The horizontal projection points were then plotted, and straight lines were drawn between them to complete the proposed well path.

PROBLEMS ENCOUNTERED

Coal Thickness

The major problem encountered, which eventually led to the abandonment of the slant hole drilling project at Mather, Pa., was the extremely erratic thickness of the Freeport coalbed. Corehole data available before the start of drilling indicated that the thickness of the Freeport coalbed was erratic in the northwest, northeast, and southeast quadrants surrounding the drill site. The coalbed in these quadrants ranged in thickness from no coal to nearly 8 feet. Seven coreholes within the prime drilling confines of S 4° W to S 85° W, and at distances of 1,300 to 22,000 feet from the surface location of the slant hole, indicated 5.9 to 8.5 feet of Freeport coalbed. The first slant hole penetration of the Freeport horizon was only about 750 feet away from a corehole (fig. 7), which indicated a thickness of 6.75 feet of coal. However, less than 0.5 foot of coal (No. 1, figs. 7-8) was encountered on the first slant hole penetration.

The first penetration of the Freeport horizon was plugged back, and a second attempt to drill into the coalbed was made with a shift of the drill path to the west to intercept the coalbed closer to the corehole containing 6.75 feet of coal. This second hole intercepted less than 0.4 foot of Freeport coal (No. 2, figs. 7-8), at a distance of 690 feet from the corehole. Drilling on this hole continued with the well path (fig. 8, top) dipping almost 8 feet below the initial contact with the coalbed, and no additional coal was encountered. The well path was controlled back up through the elevation of the original intercept and 11 feet above, with no coal encountered (No. 3, figs. 7-8). The final bottom-hole location of this hole was 386 feet out from the initial intercept and only about 520 feet from the nearest corehole (fig. 7), which had 6.75 feet of coal.

The third hole into the Freeport horizon encountered 3.4 feet of coal (No. 4, figs. 7-8). However, control problems with the Dyna-Drill resulted in intercepting the coalbed at too steep an angle to permit reaching a

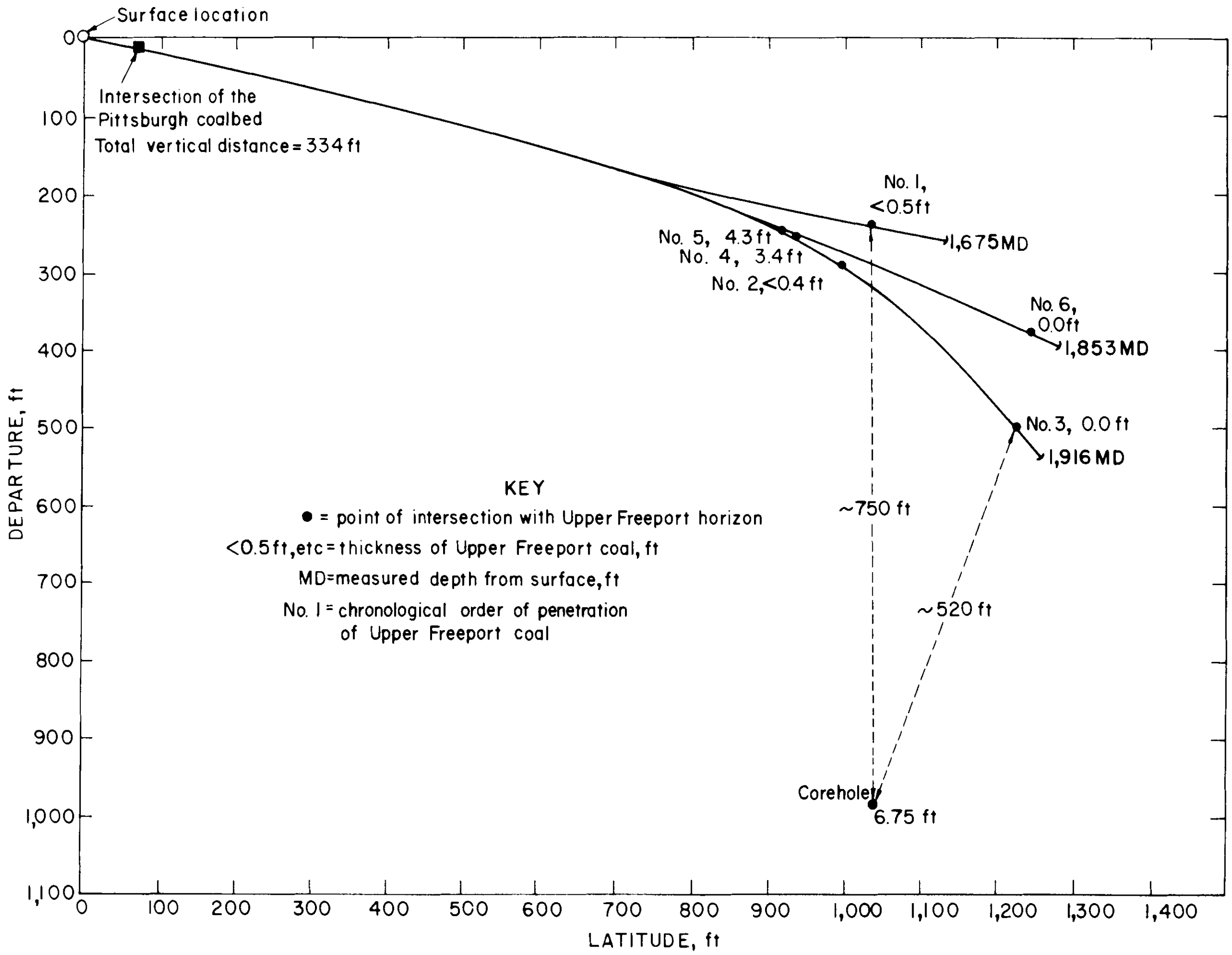


FIGURE 7. - Plan view of drill paths with coal thicknesses of Freeport horizon intercepts and nearest corehole.

horizontal drill path at the coalbed horizon within any reasonable horizontal distance. This hole was abandoned and another sidetrack begun with the intent of reentering the Freeport as close to the previous penetration as possible, but with a horizontal drill path that could be continued in the coalbed.

Control problems were again encountered with the Dyna-Drill on the next attempt to enter the coalbed horizontally. This was partly due to an attempt to use a new 2° bent sub in place of the bent housing. This sub could not build angle and was replaced with the 45-minute bent housing. It would have been desirable to shift this drill path still farther west than the previous holes; however, the problems with attempting to reach a horizontal attitude precluded controlling the azimuth of the hole. The well path entered the coalbed at a shallower angle than the previous attempt, but still not close enough to horizontal to remain within the 4.3 feet of coal (No. 5, figs. 7-8) encountered. The well path dipped 13 feet below the top of the coal before it could be brought to horizontal and controlled back to the depth of the initial

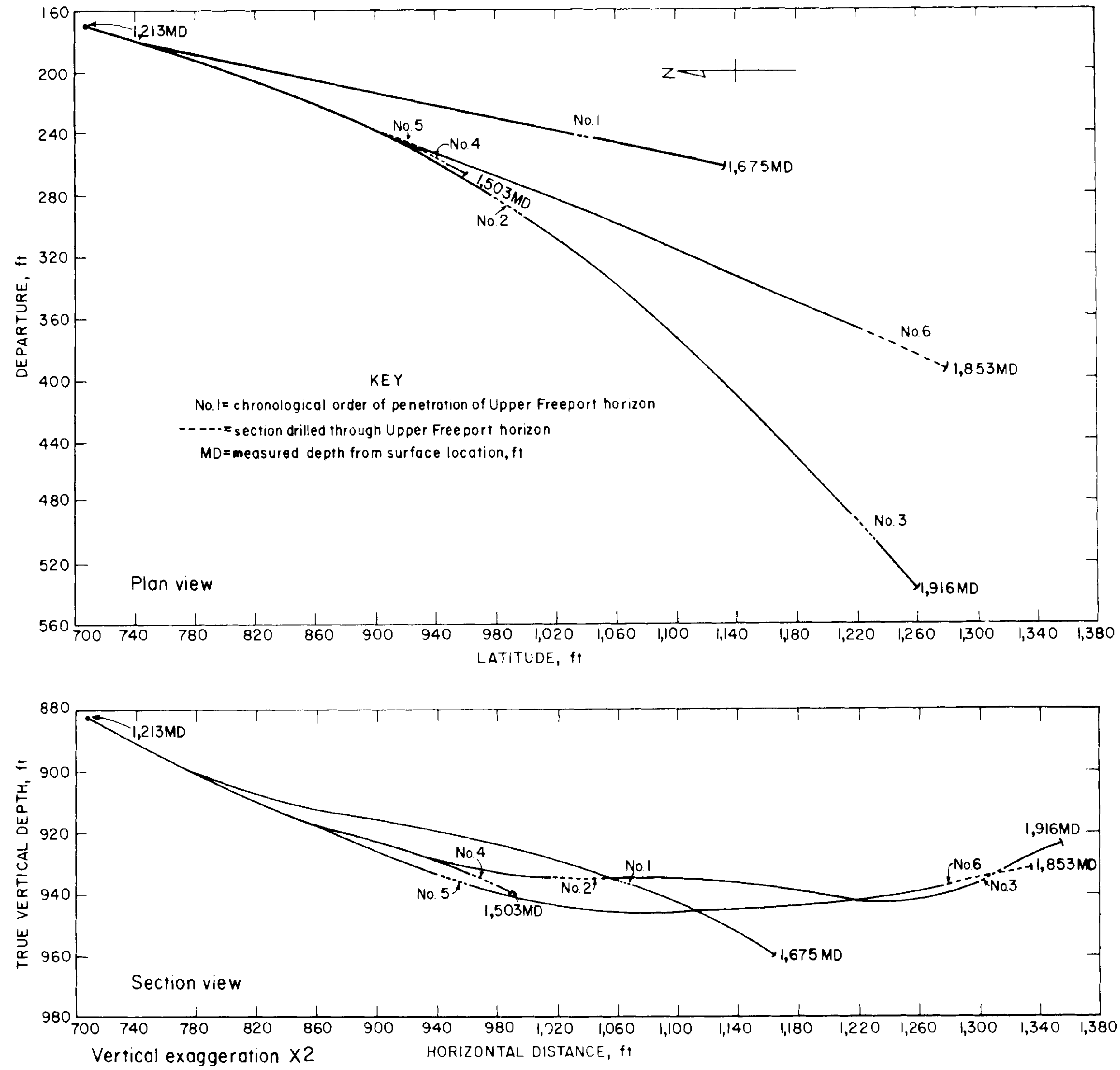


FIGURE 8. - Plan and section views of drill paths with portion drilled through Freeport horizon.

penetration. The hole was continued to a point 390 feet beyond and 1 foot above the initial penetration of the coalbed; again no coal (No. 6, figs. 7-8) was encountered. At this point, it was decided that the Freeport coalbed at the Mather, Pa., location was too erratic in thickness to support the slant hole drilling technique for degasification in advance of mining. The hole was subsequently plugged and abandoned.

Mechanical Problems

Several mechanical problems adversely affected the timely and economical completion of the pilot hole. Completion time of the pilot hole was 126 24-hour days, of which 38 days were downtime. An additional 9 days were lost for holidays, primarily at Christmas and New Year. Twenty days of the mechanically related downtime was encountered with failures of the new Dyna-Drill tool size designed for this type of drilling. Sufficient field testing of the new tool was not possible before the start of the project. The Dyna-Drill problems were mainly failures of shafts and U-joints. Spare parts for the new tools were in short supply until late in the project.

The drill rig was also newly modified for slant hole drilling and was essentially untested before being used on the project. Downtime directly due to the mechanical problems with the rig was 5 days.

Mud pump problems resulted in the loss of 3 days of drilling time. The first pump used was a small, belt-driven Bean triplex pump which was thought to be contributing to the Dyna-Drill failures by not maintaining the proper mud flow. Larger chain-driven mud pumps were then used, but they experienced many mechanical breakdowns, probably partly due to their age. (A new mud pump was ordered 11 months before the beginning of the project, but the backlog of orders precluded delivery when needed.)

Significant delays were encountered in the pilot hole drilling owing to the difficulty in maintaining the proper well path. These directional delays were in addition to those experienced at the coalbed horizon. On three occasions, between vertical depths of 860 and 880 feet, the actual well path deviated from the proposed well path to the extent that corrective measures would not bring the hole back on target in time to intersect the coalbed horizontally. These situations required the setting of a cement plug through the incorrectly drilled zone so that the hole could be sidetracked at a point that would continue the well path at the proper angle. The three sidetracks are shown in cross section and plan view in figure 9.

A total of 23 days was lost during the sidetracking operations. Extra time was lost due to problems with the cement failing to harden properly. The first plug was made with a cement grout which was allowed to set 24 hours before attempting to sidetrack. When this plug failed to harden, several combinations of cements and additives were tried before a solid plug was obtained. The final mix used was 1 part Hi-Early cement with 2 parts sand, 3 pct CaCl, and 1 pct Gel-flake to achieve a 28-second flow grout. This mixture was allowed 36 hours to harden before sidetracking.

Environmental Protection

A problem that did not result in lost time but did result in extra expenditures was the excessive noise during night drilling, which disturbed the nearby residents. Sound-baffling enclosures were constructed around the drill rig and the mud pump, and a water baffle chamber was attached to the drill rig exhaust system. These measures significantly reduced the noise

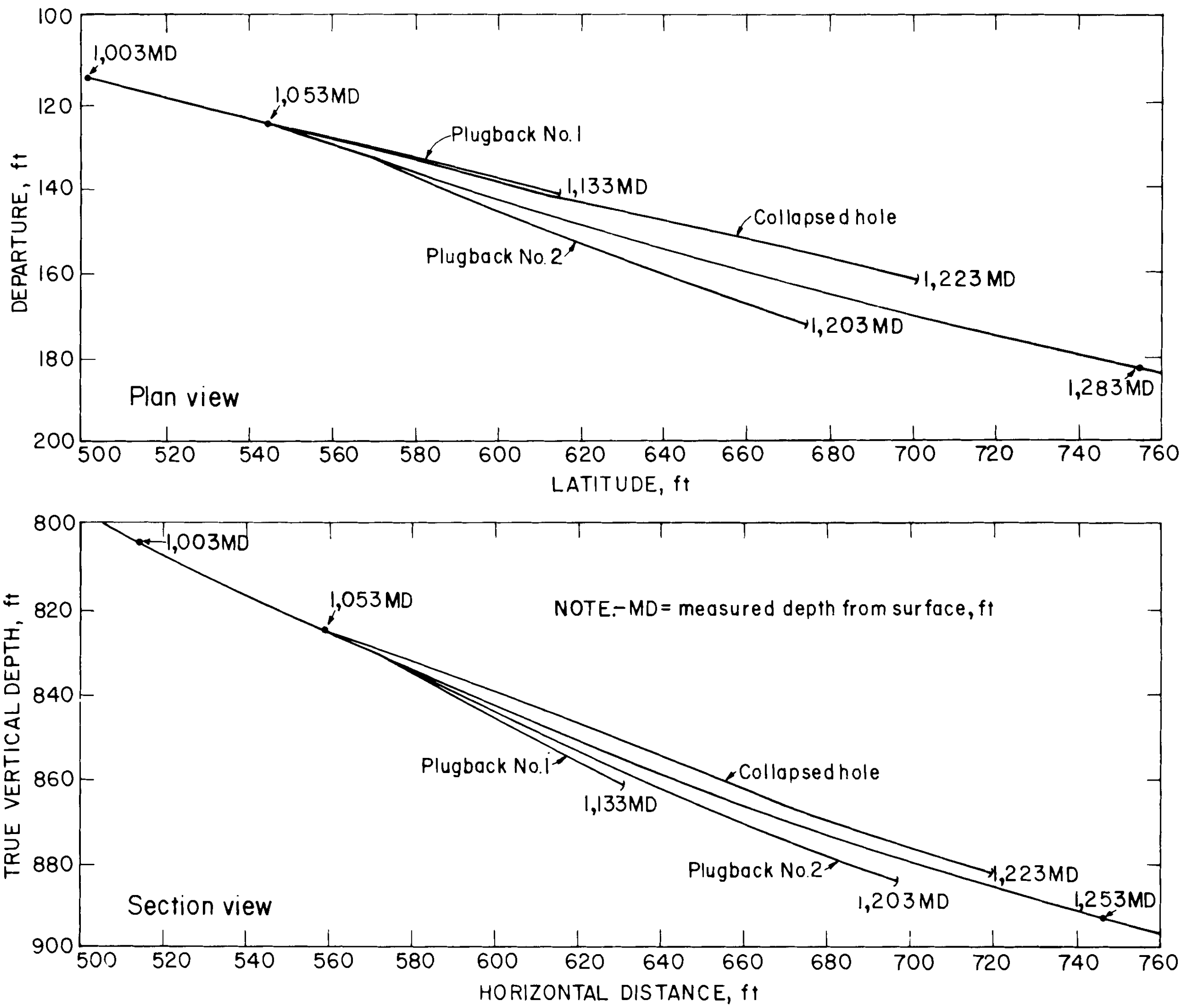


FIGURE 9. - Plan and section views of sidetracks above the Freeport coalbed.

level. Sound levels (measured 100 feet from the drill rig) during drilling operations were 70-72 decibels before baffling was installed and 63 decibels afterwards. The peaked roof of the rig enclosure was hinged so that it could be opened to lower the mast, if necessary. The enclosures were constructed and bolted together in sections to make the structures movable and reusable.

COST ANALYSIS

The project cost breakdown for the 4-1/2-month operation of the slant hole operations is given in table 2. The total cost of the project, not including the Government-owned drill rig,[6] was $385,481.

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[6] The cost of the Reed exploratory drill, purchased in 1975, was $151,000.

TABLE 2. - Project cost breakdown

Item	Cost
Rebillables:	
Physical plant:	
Site preparation	$6,439
Electrical systems and power	5,759
Fence	2,699
Office and supply trailers	1,660
Water	893
Telephone	533
Sanitation	589
Total	18,572
Directional drilling services	55,792
Dyna-Drill rental	32,401
Bits, subs, and casing	13,309
Drill, rig parts	1,446
Mud pump rental	30,857
Drilling mud	6,218
Fuel, oil, and storage tanks	5,637
Geolograph	912
Welding	1,885
Plugback and fishing equipment	1,459
Noise pollution control	2,799
Miscellaneous and small tools	4,716
Travel, transportation, and shipping	18,072
Total	194,075
General and administrative at 19.8 pct	38,427
Grand total	232,502
Labor:	
Supervisors	27,474
Drillers	22,733
Helpers	35,894
Field engineer	2,704
Other labor	7,206
Total	96,011
Labor overhead at 33 pct	31,684
Total	127,695
General and administrative at 19.8 pct	25,284
Grand total	152,979
Grand total for project	385,481

The mechanical and geological problems encountered on this research drilling project added substantially to the overall costs. For evaluation of the total project expenditures, most of the lost time can be placed into three categories: Mechanical problems, plugging and sidetracking prior to initial coal intercept, and plugging and sidetracking after initial coal intercept. The monetary effect of each of these lost-time categories on the major expense items (labor, and equipment and service rentals) is given in table 3. Approximately $111,000 was spent for extra labor and equipment rentals while drilling the 3-inch pilot hole to the first intercept of the Freeport coalbed. Slightly more than $93,000 was spent during the 46 days of exploratory drilling after the first intercept, attempting to locate a sufficient thickness of coal to support further development of the slant hole degasification technique. Deducting the approximately $204,000 unanticipated expenses from the total project expenditures, an estimate of $182,000 remains as the approximate cost of drilling the pilot hole, free from major mechanical breakdowns and without plugging and sidetracking, to the top of the Freeport coalbed at Mather, Pa.

TABLE 3. - Breakdown of major item lost-time cost

Item	Mechanical problems (29 days)	Plugging and sidetracking prior to coal intercept (23 days)	Plugging and sidetracking after initial coal intercept (46 days)	Problem-free cost	Total cost
Labor...............	$31,412	$26,036	$47,539	$47,992	$152,979
Directional drilling services...........	14,733	11,807	23,901	16,398	66,839
Dyna-Drill rental...	-	5,161	14,958	18,698	38,817
Mud pump rentals....	11,963	9,587	6,829	8,587	36,966
Total..........	58,108	52,591	93,227	91,668	295,601

A common monetary evaluation of drilling operations is the cost per foot. Approximately 3,418 total feet of pilot hole were drilled on the project at a cost of $385,400, or $113 per foot. However, most drilling delays due to the failure of new equipment and to the unfamiliarity of the drilling crew with the new technique occurred during the first 3 months of the project. Most of these problems were solved by the time the pilot hole reached the Freeport coalbed for the first time, and continuous drilling then approached a reality. The total footage drilled up to this first intercept was approximately 1,935 feet at a cost of $292,253, or $151 per foot of drilling. The total footage drilled after the intercept was approximately 1,483 feet at a cost of $93,227, or $63 per foot of drilling. This was substantially lower than both the total project average of $113 per foot and the $151 per foot average for the project's initial footage. It is hoped that the cost per foot can be further reduced with better directional control, with the increased penetration rates of new bit designs, and with the greater reliability of the improved Dyna-Drills used in the later stages of the project.

The many variables inherent in drilling operations make it virtually impossible to obtain problem-free drilling. Thus the problem-free drilling costs calculated for this particular drilling operation should not be considered an absolute estimate of cost for future utilization of the directional drilling technique. It must also be pointed out that all of these costs are for the drilling of the 3-inch pilot hole, and do not include the costs of reaming the small hole out to the required larger final size.

CONCLUSIONS AND RECOMMENDATIONS

After review of all data from the project, it is concluded that it is feasible to drill a directional hole to a predetermined target. Granted this, there is no technical reason why directionally controlled drilling cannot be used as a coalbed degasification technique.

The abandonment of the slant hole at Mather was the result of an insufficient coal thickness to maintain the horizontal drilling technique. It is essential in future projects that at least one corehole be drilled to determine the coal thickness at a location as close as possible to the projected initial coal intercept. In coalbeds where no preliminary geologic data are available, or where such data indicate that the coal varies abruptly in thickness, it will be necessary to drill additional coreholes along the projected well paths to evaluate the feasibility of slant hole degasification.

The exploratory coreholes will be useful in additional ways. By coring the entire section to be drilled, the directional driller will know in advance what rock types are likely to be encountered. The drill cuttings can be compared with the lithologic data from the coreholes to keep track of where the pilot hole is in the geologic section.

A major problem expected with the slant hole degasification technique is the dewatering of the coalbed. It has been shown in field applications and laboratory analysis (1-6) that to produce gas from coal most efficiently, the inherent water must first be removed from the coalbed. It is recommended that the coreholes drilled for geologic data be used for dewatering the coalbed. If the dewatering process can be started from the coreholes before or during the drilling of the slant hole, higher initial gas flow rates can be expected.

The cost of drilling the 3-inch pilot hole, problem free, to the top of the Freeport coalbed at Mather, Pa., is estimated to be about $182,000. It is expected that the total time to drill a pilot hole, problem free, can be reduced to approximately 80 days as a result of the increased penetration rate of new diamond bit designs and the higher reliability of the modified Dyna-Drill tool. This reduction in total drilling time will further lower the expenditures for labor, directional services, and equipment rental on the pilot hole above the coalbed.