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Drilling a Horizontal Coalbed Methane Drainage System From a Directional Surface Borehole

By David C. Oyler and William P. Diamond

UNITED STATES DEPARTMENT OF THE INTERIOR

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DRILLING A HORIZONTAL COALBED METHANE DRAINAGE SYSTEM FROM A DIRECTIONAL SURFACE BOREHOLE

by

David C. Oyler[1] and William P. Diamond[2]

ABSTRACT

Three long horizontal holes were drilled from a directionally drilled surface hole at the Emerald Mine near Waynesburg, Pa. The purpose was to adapt the technique of directional drilling for use in draining methane from coalbeds. A 504-m (1,652-ft) long, 76-mm (3-in) diameter, circular arc pilot hole was drilled, using a downhole mud motor, to enter the Pittsburgh coalbed at a vertical depth of 305 m (1,000 ft). The hole was reamed to 222 mm (8-3/4 in) and was cased to a measured depth of 486 m (1,595 ft). Three 76-mm (3-in) diameter horizontal drainage holes were then drilled, totaling 2,909 m (9,544 ft) of horizontal hole. Improvements in drilling methods increased the average drilling rate from 20.4 m (67 ft) to 64.9 m (213 ft) per day. The cost of drilling the directional and horizontal holes (using a Government-owned drill rig) was $1,169,530, a figure inflated by inexperience and by delays caused by lost-circulation problems and fishing operations. An estimated total drilling cost of $960,000 (including rental of a drill rig) for an improved system, was determined by a detailed cost analysis.

Initial gas and water production from November 1979 through May 1980 was low because of caving of the horizontal holes drilled in shale near the bottom of the casing.

BACKGROUND AND INTRODUCTION

A project to directionally drill a coalbed methane drainage system from the surface was initiated by the Bureau of Mines in 1976. Drilling activities began in September 1978 at the Emerald Mine in Greene County, Pa. (fig. 1). In October 1977, the contract was transferred to the U.S. Department of Energy, with the Bureau of Mines continuing technical management of the project. Included in the methane drainage system was a directionally drilled access hole from the surface intercepting the Pittsburgh coalbed, three long horizontal methane collection holes drilled in the coal, a vertical hole for removing water from the coalbed, and seven vertical holes to monitor the effects of the system with time. The goals of the project are to demonstrate that the technique of directional drilling can be used to drain methane from coalbeds in advance of mining, to determine the distance horizontal holes can be drilled, to obtain information to improve the technique, and to investigate coalbed reservoir mechanics.

[1]Mechanical engineer.
[2]Supervisory geologist.
All authors are with the Pittsburgh Research Center, Bureau of Mines, Pittsburgh, Pa.

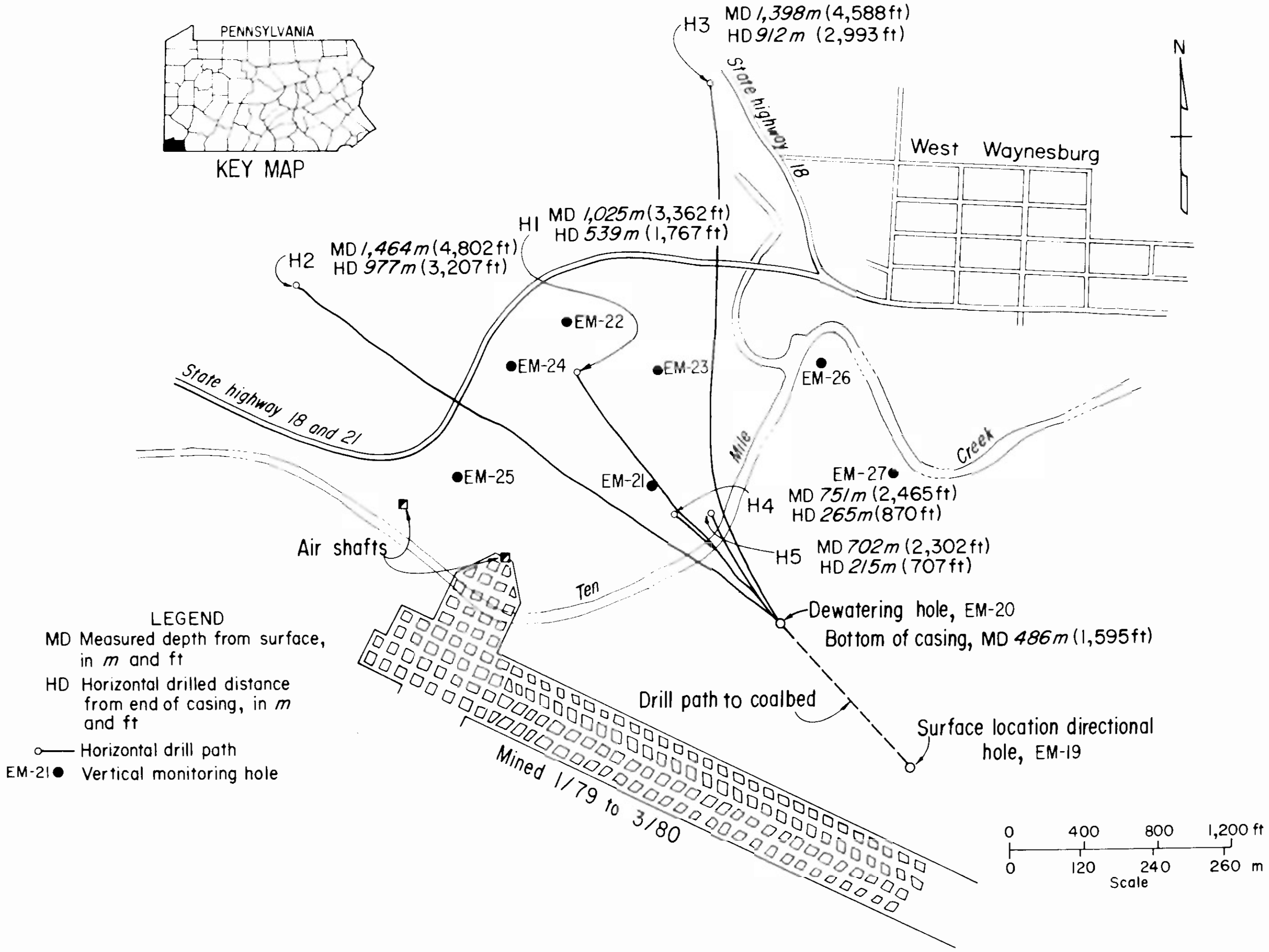

FIGURE 1. - Map of project site. The path of EM-19 and the locations of dewatering hole EM-20, monitor holes EM-21 through EM-27, and nearby mine workings are shown.

Previous publications[3] have outlined in detail the scope and goals of this and other Bureau of Mines directional drilling research. The purpose of this report is to describe the actual performance of the work at the Emerald Mine and to make recommendations for improvements in drilling methods for future systems of this type.

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[3]Diamond, W. P., and D. C. Oyler. Directional Drilling for Coalbed Degasification in Advance of Mining. Proc. 2d Ann. Symp. on Methane Recovery From Coalbeds, Pittsburgh, Pa., Apr. 18-20, 1979, pp. 162-176.

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Diamond, W. P., D. C. Oyler, and H. H. Fields. Directionally Controlled Drilling To Horizontally Intercept Selected Strata, Upper Freeport Coalbed, Greene County, Pa. BuMines RI 8231, 1977, 21 pp.

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ACKNOWLEDGMENTS

Much of the credit for the technical success attained in the Emerald directional drilling project belongs to the drilling contractor, the drilling crews, and the subcontractors. Special recognition is given to Mr. Harold F. Scott, general manager, and Mr. John Gardner, general superintendent, of the former Harold F. Scott, Contractor, Bridgeville, Pa.; Mr. Verne Nesvacil, directional drilling engineer, Eastman-Whipstock, Inc., Traverse City, Mich.; and Mr. John Workman, mining and industrial manager, Dyna-Drill Co., Irvine, Calif. The continued assistance of the Emerald Mines Corp., Waynesburg, Pa., is also gratefully appreciated.

DRILLING PROGRAM

General Drilling Plan

The general plan for drilling the directional hole was to drill a 76-mm (3-in) diameter pilot hole in a circular arc from the surface to intercept the Pittsburgh coalbed horizontally (fig. 2). The hole was to be overreamed (over the BQ wireline rod used to drill the pilot hole) to 222 mm (8-3/4-in) and then a 140-mm (5-1/2-in) diameter casing was to be cemented in place. Three 76-mm (3-in) diameter horizontal methane drainage holes (fig. 1) were then to be drilled, each up to 915 m (3,000 ft) in length fanning out from the bottom of casing. A vertical hole was to be drilled near the coalbed intercept point and equipped with a downhole plunger pump for dewatering. The vertical hole would be hydraulically stimulated to create a higher permeability path for water to flow from the horizontal hole into the vertical hole. In addition, seven vertical holes were planned for monitoring the progress of methane drainage by observing the changes in the height of a static water column over the coalbed in each hole.

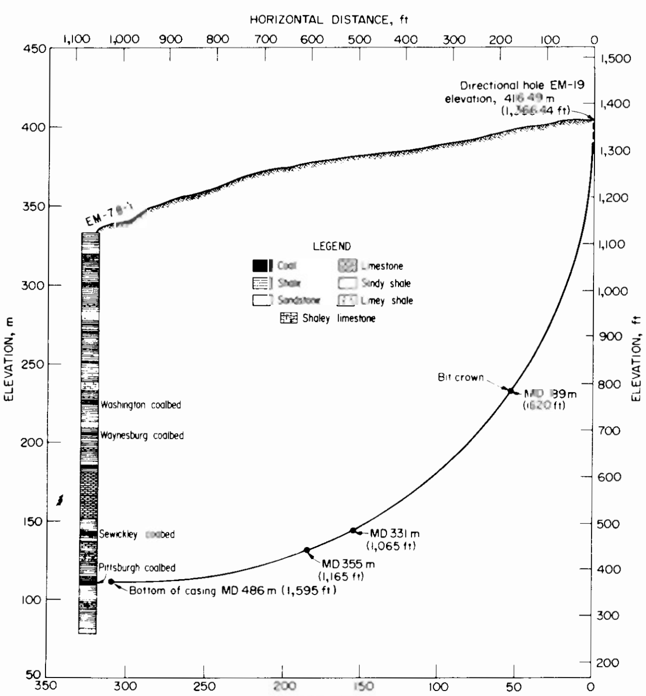

FIGURE 2. - Section view of EM-19 well path. Geologic column at left is from a corehole near well EM-20.

Site Selection and Preparation

The primary requirement of a directional drilling site is for sufficient depth of cover over the target coalbed to make the required 1.57-rad (90°) turn to enter the coalbed horizontally. At the rate of angle build desired for the directional hole, 0.34 rad/100m (6°/100 ft), the required distance was 290 m (950 ft). The drilling site selected was at the top of the highest ridge in the area to obtain the required depth of cover. The local structure of the coalbed was also downdip in the direction of drilling which added another 6 m (20 ft) to the effective vertical distance. The actual vertical distance to the coalbed, determined when well EM-20 (fig. 1) was drilled, was approximately 305 m (1,000 ft). This made it possible to start drilling with the rig's mast vertical (a definite advantage during drilling and for servicing the well) and left an additional 15 m (50 ft) to be drilled vertically before beginning to deviate the hole. Part of this distance was used to set conductor pipe in the hole.

Two additional requirements of the site were a location that would allow a vertical hole to be located at the coalbed intercept point, and a site situated such that the horizontal holes would be far ahead of mining, but if possible still located where the hole would have a measurable effect on methane emissions in the mine. These requirements greatly restricted the number of available sites and the allowable drilling directions for the site chosen, but the site met all three requirements. The EM-19 site was located so that when on production it would shield the Emerald mine from migrating gas (fig. 1), but the horizontal holes were not within the area of future mine development. This meant that the methane drainage life of EM-19 could be as much as 10 to 40 years.

The surface location requirements were for good access roads, security from vandalism, nearby electrical power, sufficient site area for all equipment, a nearby source of water, and a nearby pipeline for gas sales once production began. Since the site chosen was on mine property and was located near an existing road, security, site access, and access to power were easily arranged. Water for mixing drilling fluids (mud) had to be hauled from hydrants about 300 m (1,000 ft) away, but originally this was not considered a serious problem. The lack of a convenient water supply was to be expected on a hilltop site. Fortunately a gasline passed within 60 m (200 ft) of the site, simplifying the gas piping requirements. The Emerald Mines Corp. also cleared a site large enough for all drilling and completion activities (figs. 3-4).

The site preparation consisted of clearing the trees from an area

FIGURE 3. - Drilling site before preparation. Photograph taken March 1978, view is east.

FIGURE 4. - Drilling location after site preparation. Mud pits in foreground. Photograph taken August 1978, view is northwest.

approximately 120 m (400 ft) by 45 m (150 ft). A divided mud pit 26 m (85 ft) long, 6 m wide (20 ft), and 2 m (6 ft) deep was then dug. The site was then covered by about 30 cm (1 ft) of crushed stone which was rolled and compacted. Figure 4 shows the site in August 1978 shortly after the preparation work was completed. A plan view of the site, after the drilling equipment was set up in November 1978, is shown in figure 5.

A major difficulty with the EM-19 drilling site, which will be discussed in more detail in the "Pilot Hole Drilling" and "Reaming" sections, was the ridgetop location which put the site above the local water table. Several fractured and solution channeled limestones became severe lost circulation zones that created major difficulties in drilling until the hole was finally cased.

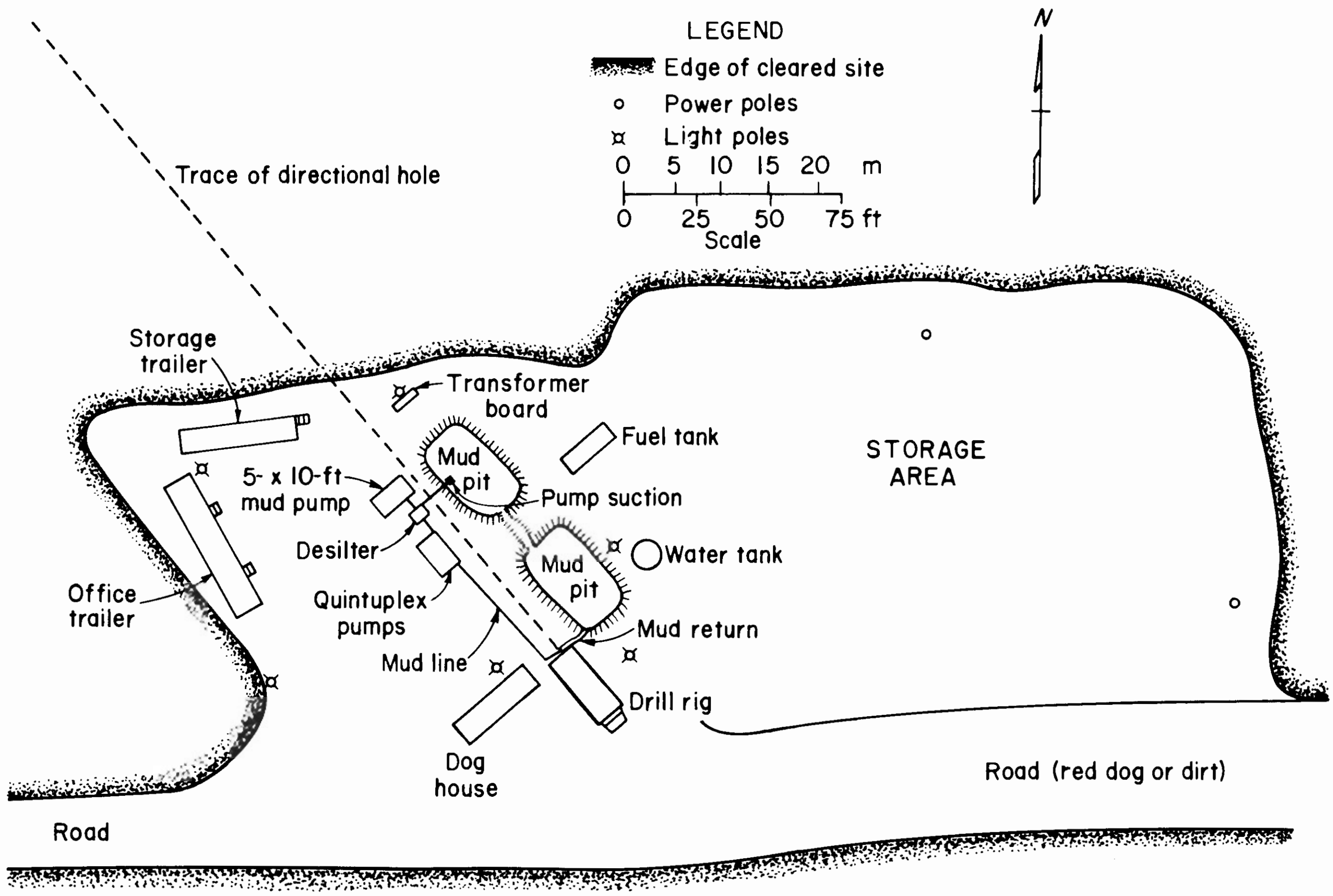

FIGURE 5. - Plan view of EM-19 drilling site.

Drilling Rig

The drilling rig used to drill the directional hole was a Reed Tool Co. exploratory rig[4] (fig. 6). The rig is hydraulically operated, and powered by a Cummins model NT-855-P380, 283-kW (380-hp) diesel engine. The rig has two hoist cylinders giving it a 311-kN (70,000-lb) hoist capacity, and a 10.5-m (35-ft) stroke. It was originally purchased in 1974 for the Bureau of Mine's Mather directional hole project.[5]

The primary requirements for the drilling rig were a 10.5-m (35-ft) stroke, an ability to finely adjust the drill pipe feed rate and bit weight, and a "pulldown" capacity (the ability to put additional weight on the bit). The pulldown capacity is necessary to push casing through tight spots. The stroke length is required to handle casing and drill pipe for reaming. The fine feed capacity is needed when running downhole motors to prevent stalling and damaging the tools. Two other desirable features, which the Reed rig did not have, were tongs and breakout tools for handling large drill pipe and a wide drill table to allow easy handling of bits and subs greater than 305 mm (12 in) in diameter. This made it difficult to ream and case the hole to shut off the lost-circulation zones near the surface.

[4]Reference to specific equipment, trade names, or manufacturers does not imply endorsement by the Bureau of Mines.
[5]Third work cited in footnote 3.

FIGURE 6. - Drilling rig. Note survey tool and wireline hoist in right foreground. Photograph taken during pilot hole drilling operation, November 1978.

Pilot Hole Drilling

The directional hole was begun by rotary drilling a 318-mm (12-1/2-in) diameter vertical surface hole to the top of bedrock and installing 3.7 m (12 ft) of 267-mm (10-1/2-in) diameter conductor pipe. A 159-mm (6-1/4-in) diameter tri-cone rock bit was then used to rotary drill the hole to 15 m (50 ft) where directional drilling was to begin.

Directional Drilling Equipment and Control Techniques

The directional drilling was done using a 60-mm (2-3/8-in) diameter Dyna-Drill tool, a 76-mm (3-in) diameter bit, and 56-mm (2-3/16-in) o.d. BQ wireline drill rod (3.3-m (10-ft) joints). The Dyna-Drill (fig. 7) is a positive displacement motor with a helical drive shaft that rotates when fluid is pumped through the tool. Rotation of the drive shaft is transmitted through universal joints to the shaft of a bit sub. Sealed bearings support the shaft of the bit sub. The housing of this sub is also bent at a small angle to provide directional control. Both the universal joints and bearings are expendable items, typically requiring replacement at 50- to 100-h intervals. Drilling fluid was supplied to the tool by two FWI 5P-200A quintuplex pumps.

The Dyna-Drill will build angle at a rate roughly proportional to the size of the bend of the housing. The rate is also affected to some extent by the type

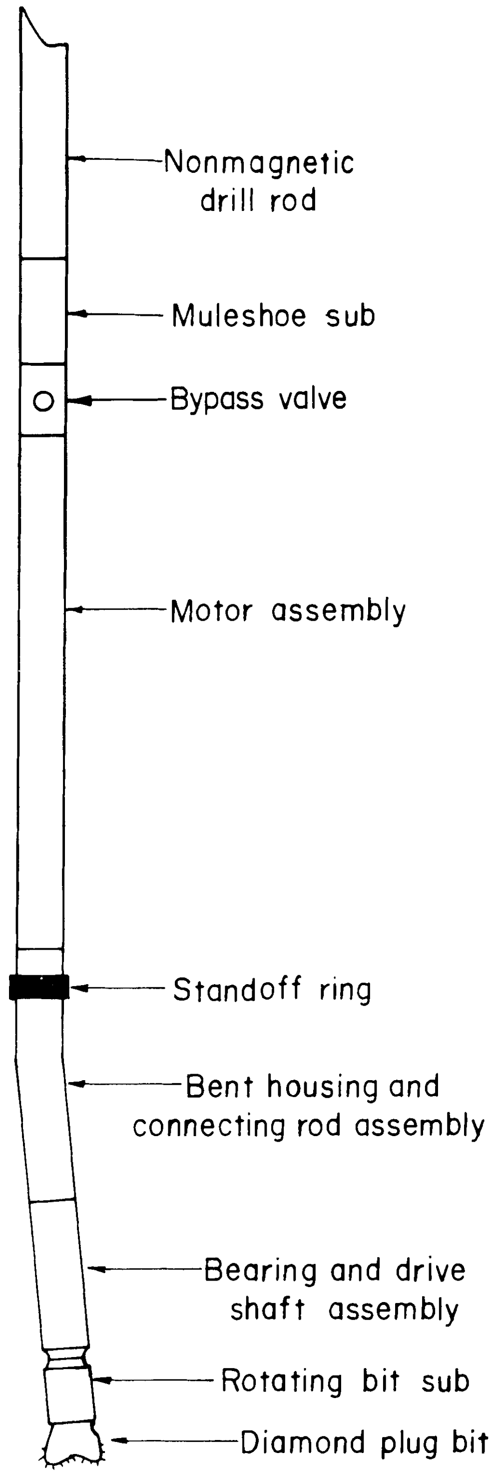

FIGURE 7. - Dyna-Drill tool and drilling assembly.

of formation drilled, the hole inclination, the orientation of the bend, and the weight on the bit. During the Mather directional drilling project,[6] the rate of angle build was controlled primarily by weight on the bit as determined by the pump pressure. (As bit weight increases, the differential pressure across the water courses of the bit increases.) Changes in weight on the bit also affect the penetration. When rapid angle build rates are desired, bit weight can be high and penetration is satisfactory. But when the angle build rate must be reduced, then the bit weight must be decreased and the penetration decreases.

To eliminate the loss of penetration caused by decreased bit weight, the pilot hole at the Emerald Mine was controlled primarily by changing bent housings. Four assemblies were used. In order of increasing build rate capability they were a 0.0087-rad (30-min) bent housing, a 0.013-rad (45-min) housing, and both of these housings with standoff rings added. The values of the angles are nominal values. The true bend of a particular housing often varied from its stated angle. By using different bends instead of varying the bit weight, it was possible to use the most efficient bit weights (measured by the pump pressures) and flow rates through the Dyna-Drill to obtain the maximum penetration rate (it also made it possible to correlate penetration rates to formation types).

To minimize the number of trips made to change bent housings, the directional drilling engineer continually made projections of the well path. In this way it was possible to determine the effect a particular assembly would have on the well path and to plan the use of future housings to make corrections to bring the hole back on course. For example, if one assembly built angle at 0.40 rad/100 m (7°/100 ft) it might be used for 30 m (100 ft) and then a housing that gave a lower build rate would be used to bring the hole back on line, or

[6]Third work cited in footnote 3.

slightly below it. The high-build housing would then be put back on and the cycle begun again.

The actual position of the hole and the direction of the bend were determined by the use of a small-diameter magnetic singleshot surveying tool. This tool is run on a wireline and contains a compass on a pivot and a camera to allow the azimuth of a reference point in the tool and the tool inclination to be recorded on film. A subassembly in the drill string with a pin in it and a cam on the survey tool (known as a muleshoe) forces the survey tool to line up in the same relative orientation with the drill string on each survey. This makes it possible to use the survey tool to aline the bent housing in the desired direction. Because the singleshot tool has a compass, it must be used with nonmagnetic drill pipe. The bottom 24 m (80 ft) of BQ rod was made of nonmagnetic stainless steel as were the housings of the Dyna-Drills.

The output of the singleshot tool is (1) a reading of the well path azimuth, (2) the hole inclination, and (3) the azimuth of the drill string reference point. Given the position of the previous survey point, the new measured depth, and items 1 and 2, the hole position can be determined trigonometrically. The survey positions in EM-19 were computed by the radius-of-curvature method. The drill string reference information allows the drill string to be properly oriented to keep the hole along the proper well path.

During the course of drilling the directional drilling engineer determined the characteristics of each bent housing assembly in an attempt to find one that would give as close to a 0.34-rad/100 m (6°/100 ft) build rate as possible. In general, it was found that no assembly gave this angle-build rate, so the occasional changing of housings was required. However, it was often possible to program the drilling so that housings were changed when a bearing package or universal joint had reached the end of its useful life or when a pipe trip was required for some other reason. This constant preplanning of the drilling, the use of gradual hole corrections, and the method of allowing each housing to build angle at its natural rate actually reduced the "doglegs" (sharp angle changes) in EM-19 compared to directional holes drilled previously. Of the 16 pipe trips made during pilot hole drilling, 4 were made because of lost circulation, 5 because of Dyna-Drill failures, and 2 because of failures of other equipment. The remaining five trips were made exclusively to change bent housings. However, a total of 10 changes of housings were made, so that the housing changes were doubled up with other operations about one-half of the time.

The EM-19 pilot hole was drilled without sidetracks or plugbacks being required by the hole going off course. There was only one section of hole with severe doglegs. This took place from 330 to 355 m (1,085-1,165 ft) measured depth (MD) (fig. 2) and was caused by the backoff and rotation of a joint of the BQ drill pipe above the Dyna-Drill, which rotated the Dyna-Drill tool face. This portion of the hole was drilled off course between 331 and 343 m (1,065-1,125 ft) MD and the subsequently required sharp well path correction caused the dogleg section to continue to 355 m (1,165 ft) MD. The doglegs in this section ran from 0.57 to 0.80 rad/100 m (10°-14°/100 ft). Fortunately, no problems were encountered either in reaming the hole or in running casing through this section of the hole.

FIGURE 8. - Strata-Pax bit, 76-mm (3-in), type 128181. Bit length 15 cm (5.9 in).

Drilling Rates and Bit Performance

Because of the control techniques used, it was possible to determine and then stay at the optimum flow rate and pump pressure through the Dyna-Drill tool to give the maximum drilling rate. Early in the drilling operation it was found that the 5.5-m^3/h (24-gal/min) and 3,500-kPa (kilopascal) (500-lb/in^2g) values recommended by the Dyna-Drill engineers were not the most efficient. Table 1 shows the differences in penetration caused by varying pressure and flow rates through the tool. This table also compares the performance characteristics of the two types of bits used to drill the pilot hole. The first Strata-Pax bit (a bit using tungsten carbide disks impregnated with diamond dust), (fig. 8) averaged 40.5 min/m (12.3 min/ft) between 15 and 135 m (50-442 ft) MD, with flow rates varying greatly from 5.5 to 13 m^3/h (24-57 gal/min), and pump pressures varying from 2,750 to 4,800 kPa (400-700 lb/in^2g). The most common flow rate during this period was 9.1 m^3/h (40 gal/ min) and the most common pressure was 3,450 to 4,100 kPa (500-600 lb/in^2g). From 135 to 162 m (422 to 530 ft) MD the parameters were held relatively constant at 3,450 kPa (500 lb/im^2g), and 5.5 to 7.5 m^3/h (24-33 (gal/min). This gave the lowest penetration rates experienced in all of the pilot hole drilling. The values of 9.5 m^3/h (42 gal/min) and 3,450 to 8,900 kPa (500 to 900 lb/in^2g) were finally decided upon as being the most efficient.

TABLE 1. - Penetration versus drilling parameters (pilot hole)

Drilling interval	Hole interval drilled		Distance drilled		Drilling time, min	Average drilling rate		Average pump pressure range		Average pumping rate range	
	m	ft	m	ft		min/m	min/ft	kPa	lb/in^2g	m^3/hr	gal/min
STRATA-PAX BIT, TYPE 128181, SN-8S46823[1]											
First[2].......	15-135	50- 442	125	412	5,065	40.5	12.3	2,750-4,800	400-700	5.5-13.0	24-57
Second.......	135-162	442- 530	27	88	1,693	62.7	19.2	2,750-3,800	400-550	5.5- 7.5	24-33
Third[3].......	162-281	530- 923	120	393	4,095	34.1	10.4	3,450-4,800	500-700	8.6- 9.5	38-42
Fourth.......	281-312	923-1,023	30	100	838	27.9	8.4	4,100-6,200	600-900	8.6- 9.5	38-42
Total...	15-312	50-1,023	303	993	11,484	37.9	11.6	2,750-6,200	400-900	5.5-13.0	24-57
DIAMOND BIT, TYPE 147496, SN-8S54001[4]											
Fifth........	312-348	1,023-1,143	36	120	607	16.9	5.1	6,200	900	9.5	42
Sixth[5].......	348-391	1,143-1,283	43	140	1,354	31.5	9.7	4,500-4,800	650-700	9.1	40
Total...	312-391	1,023-1,283	79	260	1,961	24.8	7.5	4,500-6,200	650-900	NAp	NAp
STRATA-PAX BIT, TYPE 128181, SN-8S55183											
Seventh......	391-434	1,283-1,423	58	140	1,644	28.3	11.7	4,500-4,800	650-700	9.1	40
Eighth[6]......	434-504	1,423-1,652	70	229	479	6.8	2.1	3,450-4,500	500-650	9.1	40
Total...	391-504	1,283-1,652	112	369	2,123	19.0	5.8	3,450-4,800	500-700	NAp	NAp
ALL BITS											
Total...	15-504	50-1,652	494	1,622	15,775	31.9	9.7	2,750-6,200	400-900	5.5-13.0	24-57

NAp Not applicable.
[1]Upon completion of drilling, face was worn but bit was in gage.
[2]Also drilled 6 m (20 ft) of concrete.
[3]One pax lost in this interval.
[4]Upon completion of drilling, bit was in nearly new condition.
[5]Primarily drilling limestone.
[6]Primarily drilling coal and shale.

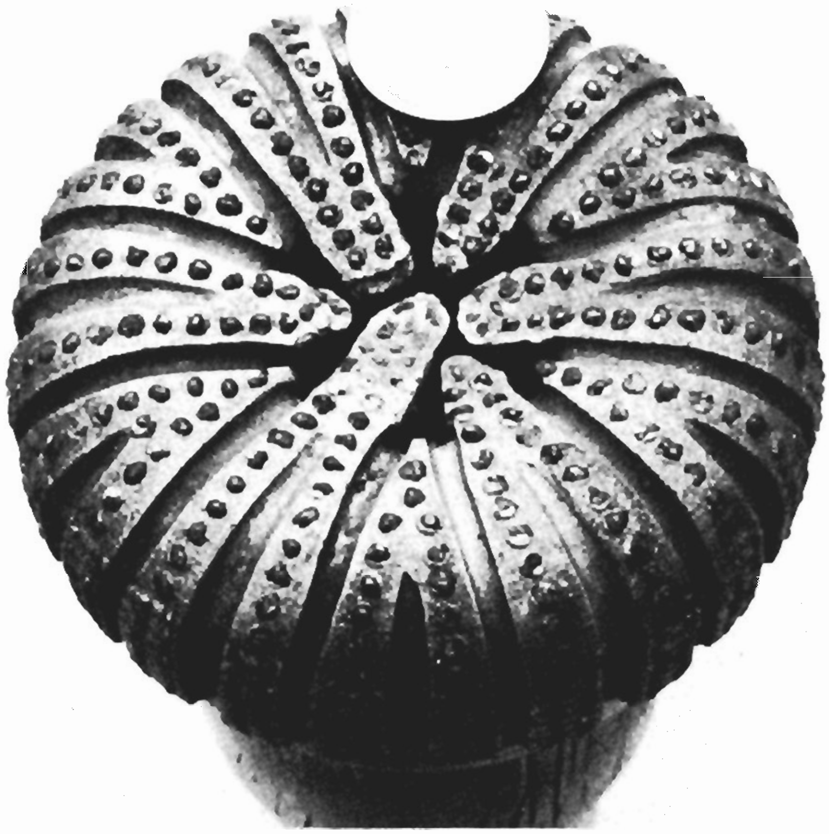

FIGURE 9. - Diamond bit. Type 147496, 76-mm (3-in) diameter.

It should be noted that the use of flow rates higher than for which the tool was designed results in a corresponding increase in the stresses on the bearings, universal joints, and shafts. This means that failure and replacement of these components will happen more often. It was felt that during pilot hole drilling the timesaving from increased penetration made these costs acceptable. However, during horizontal drilling in coal, where a pipe trip often took as long as 12 hours, and where the tool could drill nearly as fast (0.15-0.6 m/min or 0.5-2.0 ft/min) at 5.5 m^3/h (24 gal/min), as at 11 m^3/h (48 gal/min), this loss of tool life was not considered acceptable.

It can be seen from table 2 that the Strata-Pax bits generally drilled more effectively in soft formations (shales) than diamond bits. The diamond bits (fig. 9) drilled better in the hard formations such as limestones and sandstone. Overall, the efficiency of the two bit types was comparable and the choice of one over the other would basically be a matter of cost. Table 3 shows the distances drilled and net cost for each of the 76-mm (3-in) diameter bits used in both pilot and horizontal drilling. The average per meter cost of a Strata-Pax bit in pilot hole drilling was roughly \$6.50 (\$1.98/ft). The diamond bit cost per meter cannot be determined exactly but it would be between \$2.00 and \$6.50 (\$0.61-\$1.98/ft). This indicates that diamond bits were more economical (similar results can be seen when comparing the bits in horizontal drilling in coal).

TABLE 2. - Selected penetration rates versus formation types

Bit type	Measured depth		Drilling rate		Distance on bit		Estimated pump pressures		Formation
	m	ft	min/m	min/ft	m	ft	kPa	lb/in^2g	
Strata-Pax 1	36.6- 39.6	120- 130	112.9	34.4	27.4	90	3,400	500	Cement.
Do........	78.6- 80.5	258- 264	23.6	7.2	69.5	228	4,100-4,800	600-700	Shale.
Do........	84.4- 86.3	277- 283	26.2	8.0	75.3	247	4,100-4,800	600-700	Limestone.
Do........	208.5-210.3	684- 690	17.1	5.2	199.3	654	4,100-4,800	600-700	Sandstone.
Diamond.....	317.0-320.0	1,040-1,050	24.3	7.4	5.2	17	6,200	900	Shale.
Do........	345.3-347.5	1,133-1,140	17.7	5.4	33.5	110	6,200	900	Limestone.
Do........	354.5-355.7	1,163-1,167	35.4	10.8	42.7	140	4,500-4,800	650-700	Shale.
Do........	361.2-364.2	1,185-1,195	24.6	7.5	49.4	162	4,500-4,800	650-700	Limestone.
Strata-Pax 2	437.4-439.5	1,435-1,442	18.7	5.7	46.3	152	4,500-4,800	650-700	Shale.
Do........	482.2-485.2	1,582-1,592	3.3	1.0	91.1	299	3,400-4,500	500-650	Coal.

TABLE 3. - Bit costs--pilot and horizontal holes

Purchase date	Initial cost, dollars	Salvage value, dollars	Net cost, dollars	Depths drilled m	Depths drilled ft	Total distance drilled m	Total distance drilled ft	Cost dollars m	Cost dollars ft
STRATA-PAX, TYPE 128181, SN-8S46823									
November 1978	1,929.50	None	1,929.50	[1]15- 312	[1]50-1,023	297	973	6.50	1.98
STRATA-PAX, TYPE 128181, SN-8S55183									
November 1978	1,847.25	None	1,847.25	[1]391- 504 [2]487- 571 [2]729-1,025	[1]1,283-1,652 [2]1,597-1,872 [2]2,392-3,362	497	1,614	3.72	1.14
DIAMOND 3-INCH SHALLOW CONE, TYPE 147496, SN-8S54001									
January 1979.	1,376.98	644.06	732.92	[1]312- 391 [2]571- 802 [2]674- 729	[1]1,023-1,283 [2]1,872-2,632 [2]2,212-2,392	366	1,200	2.00	0.61
DIAMOND 3-INCH DEEP CONE TYPE 147464, SN-8S54000									
November 1978	1,427.00	931.08	495.92	[3]498- 549 [5]498-1,399 [3] [6]833-1,464	[3]1,632-1,802 [5]1,632-4,588 [3] [6]2,732-4,802	([4])	([4])	([4])	([4])
DIAMOND 3-INCH SHALLOW CONE TYPE 20-186-037S SN-9S52953									
August 1979..	1,735.45	978.37	757.08	[3]827- 833 [6] [7]583- 740 [6] [7]717- 752 [6] [8]501- 562 [6] [8]552- 702	[3]2,712-2,732 [6] [7]1,912-2,428 [6] [7]2,352-2,465 [6] [8]1,642-1,842 [6] [8]1,812-2,302	1,992	6,535	0.63	0.19
DIAMOND 3-INCH SHALLOW CONE TYPE 20-186-037S, SN-9S49743									
June 1979....	1,770.63	[9]0	1,770.63	[3]549- 702 [3]610- 691	[3]1,802-2,302 [3]2,002-2,266	233	764	7.60	2.32
ALL BITS									
Total or Average.	10,086.81	2,553.51	7,553,30	NAp	NAp	3,380	11,086	2.23	0.68

NAp Not applicable.
[1]Pilot hole.
[2]Horizontal hole, H1.
[3]Horizontal hole, H2.
[4]Cost included with following bit.
[5]Horizontal hole, H3.
[6]Insufficient records to determine which of these two bits drilled these intervals.
[7]Horizontal hole, H4.
[8]Horizontal hole, H5.
[9]Bit lost in hole.

Drilling Summary

The directional pilot hole was begun on November 9, 1978, at a depth of 15 m (50 ft) and was completed on December 19, 1978, at a total measured depth of 504 m (1,652 ft). Drilling was done 24 hours per day on weekdays and the job was shut down on all but one weekend. The pilot hole drilling operation was completed in 965 hours (or 40 calendar days). Of this time 240 hours were off days, 262.5 hours were spent drilling, 86 hours surveying, 38 hours in normal maintenance, 43 hours tripping pipe to change bent housings, and 295.5 hours were downtime (appendix A). The actual time required to drill the pilot hole was the sum of all of these except the downtime and the off days, or a total of 429.5 hours (about 18 days). The average drilling rate was 28 m/d (92 ft/d).

Problems were encountered in the pilot drilling with the mud pumps, the rig, the Dyna-Drill, the drill pipe, and with lost circulation. The mechanical problems, especially those of the mud pumps, were primarily those normally to be expected in breaking in new equipment and were minor (appendix A). However, about 87 hours were lost both directly and indirectly to lost circulation. Although this represents only 9% of the total time spent in pilot hole drilling it was an indication of greater lost-circulation difficulties ahead in the reaming operation. Also, not only was lost circulation expensive in project hours but the costs for water and mud were also extremely high ($31,000 for pilot hole drilling). The problem continued during the reaming operation.

The drilling fluid originally used was a Dextrid and XC Polymer mud (fig. 10) designed to decrease fluid loss, to be low in solids, and to act as a gel to aid in cuttings removal. This type of mud had proven to be very effective during the drilling of the Mather directional hole.[7] However, the lost-circulation zones in EM-19 proved to be too much for the mud's sealing capabilities. In order to slow down fluid loss, such additives as cottonseed hulls, cellophane flakes, and ground walnut shells were put in the mud. All were lost in the hole. The pilot hole drilling was completed using essentially pure water with little or no circulation.

Attempts were also made to treat the lost-circulation problem with cement and later with "gunk squeezes." Two cement plugs were set in the first 34 m (110 ft) of the hole, but they were difficult for the Dyna-Drill to drill through and were not effective, so their further use was abandoned. A gunk squeeze consists of pumping or pouring a slurry of powdered bentonite clay, diesel fuel, and (sometimes) cottonseed hulls into the hole. When the slurry comes in contact with water (presumably in the fractures of the formation taking fluid), the bentonite swells and the slurry expands to become a highly viscous gel that is difficult to move. The gunk squeezes were continued regularly through the pilot hole drilling operation and in the reaming operation. They helped to reduce fluid losses, but did not completely shut off the problem zones.

After the pilot hole was completed, a string of used BCQ wireline rod (similar to BQ rod) was run in the hole, to be used as a guide string for overreaming bits that opened the hole to 222 mm (8-3/4-in) in diameter.

A gamma-ray log of the hole was also run through the guide string before the reaming operation was begun. This log was interpretated to show that the hole had entered the top of the Pittsburgh coalbed. When horizontal drilling was begun it was found that the hole was actually 0.5 to 1 m (2 to 3 ft) above the coalbed.

[7]Third work cited in footnote 3.

FIGURE 10. - Mixing Dextrid-Polymer mud for pilot hole drilling. Sacks of Dextrid at left, FWI pumps at center, and Gardner-Denver pump at right.

Reaming

Reaming was begun on January 8, 1979. Operations were carried out on a 24-h basis with weekend shutdowns. A string of 25.4-mm (1-in) pipe was first run inside the BCQ rod, installed earlier, to stiffen it. The reaming was done using a rented string of 89-mm (3-1/2-in) diameter drill pipe with I. F. connections. Both Strata-Pax and diamond drill bits were used (fig. 11). The first reaming bits (two of an eventual five) used were 222-mm o.d. by 63-mm i.d. (8-3/4 by 2-1/2 in).

Lost Circulation

Because of the problem of lost circulation experienced in the pilot hole drilling, a high viscosity bentonite (gel) mud with lost-circulation additives was used at the start of the overreaming operation. The additives included cottonseed hulls, cellophane flakes, and ground walnut shells. The Strata-Pax bit used to begin the reaming was designed to allow the circulation of large pieces of solid lost-circulation material (fig. 11). In spite of the precautions taken to prevent lost circulation, all of the 30 m^3/h (130 gal/min) mud volume being pumped was being lost by the time the hole had been overreamed to 12 m (40 ft) MD. The hole was then drilled blind (without circulation) for several days until reaming reached a measured depth of 62 m (205 ft).

In an effort to permanently stop the lost-circulation problem encountered near the surface, the upper 35 m (115 ft) MD of the hole were reamed to a 254-mm (10-in) diameter and an attempt was made to run 245-mm (9-5/8-in) diameter casing to 34 m (110 ft) MD to shut off what was

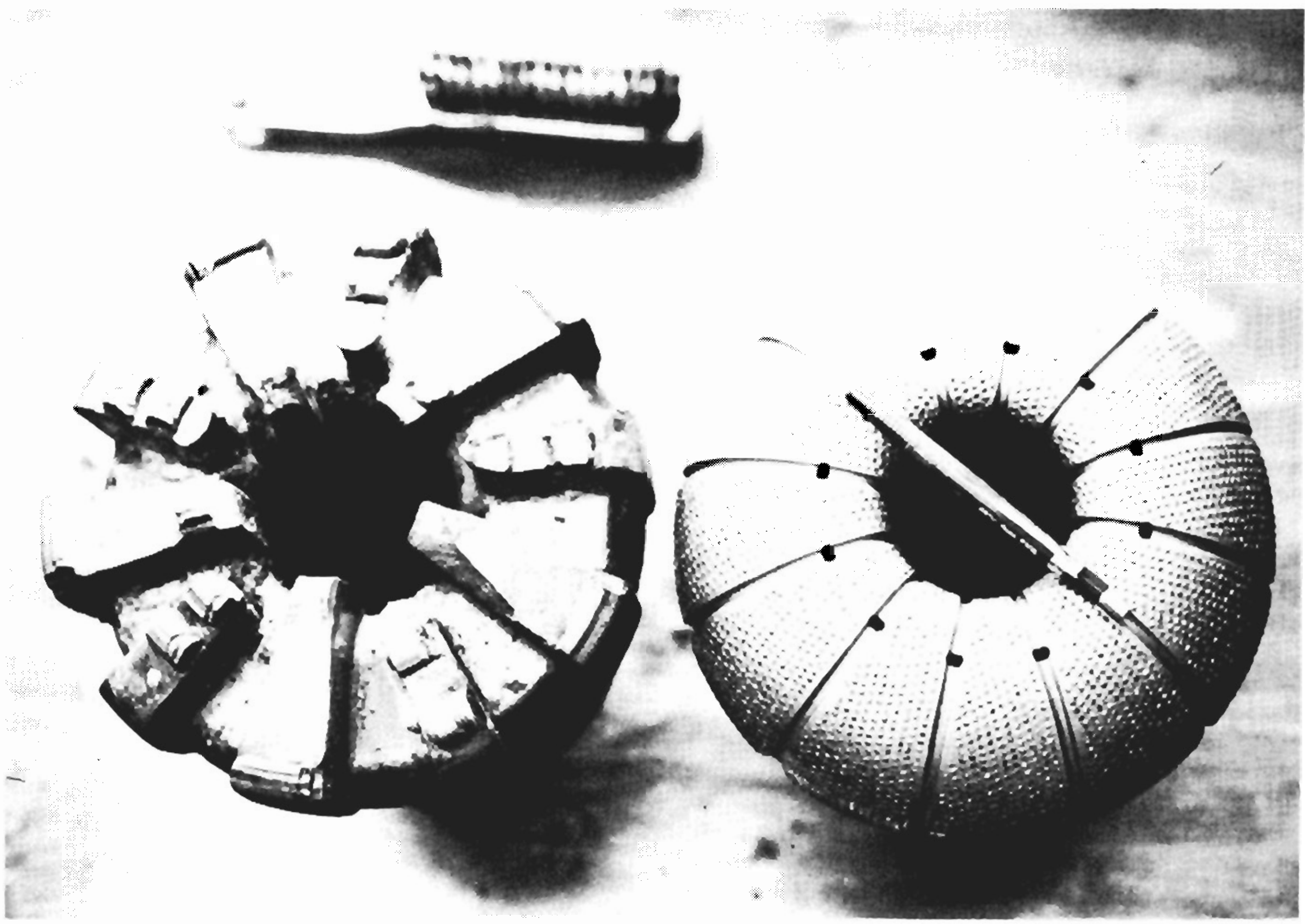

FIGURE 11. - Reaming bits. Strata-Pax at left shows matrix damage after drilling 83 m (273 ft).

believed to be the main problem zone at 27 to 31 m (90-100 ft) MD. The casing was welded to eliminate the larger diameter of the casing collars. The pipe hung up in the hole at 27 m (88 ft) MD and a fishing operation was required to remove it from the hole. At the same time as the fishing operation, the turbocharger of the rig malfunctioned and it had to be replaced. It was not until January 30, 1979, that the rig was repaired and the casing removed from the hole. Once this was accomplished the hole was again reamed, this time to 279-mm (11 in) in diameter to a depth of 36.6 m (120 ft) and 245-mm (9-5/8-in) diameter casing, with collars, was set at a depth of 34 m (111 ft).

This casing did not solve the lost circulation problem and blind drilling was continued until a measured depth of 101 m (331 ft) MD was reached. At that time the valves of the Gardner-Denver 5x10 FCFXD duplex pump required replacement and since new valves were not immediately available a switch was made to air and foam drilling. In addition, at 83 m (273 ft) MD the matrix material of the first bit (the Strata-Pax bit) began to come apart and it was replaced by a diamond bit (fig. 11 shows the Strata-Pax bit after it began to come apart and the diamond bit just before it went in the hole). Overreaming with foam was continued until a measured depth of 147.5 m (484 ft) MD was reached, although the use of foam did not adequately lubricate or cool the bits. At 147.5 m (484 ft) MD, when the new pump valves had been received and installed, another attempt was made to drill with mud. This time a salt-saturated mud was used to prevent the pits from freezing. Again circulation was immediately lost. The use of gunk squeezes, which had reduced fluid losses during pilot hole drilling, was reinstituted. These treatments sometimes helped for short periods of time, a few hours or as much as a day, but often were completely ineffective.

Fishing Operations

The use of gunk squeezes eventually led to BCQ rod being stuck inside the drill pipe. Attempts to free the BCQ from the drill pipe caused both the 25.4-mm (1-in) pipe and the BCQ rod to back off (unscrew) in the hole and a number of fishing trips over a 2-day period were required to obtain a continuous string of 25.4-mm (1-in) pipe to the surface. The BCQ had backed off at about 90 m (300 ft), but no attempt was made to screw into the BCQ rod, since the 25.4-mm (1-in) pipe was continuous to the surface.

On February 21, 1979, a new Strata-Pax bit (fig. 12) was received and was immediately run in the hole to replace the diamond bit that had been worn out. The new bit began reaming at a measured depth of 186.5 m (612 ft). It had reamed only 2.5 m (8 ft) when the bit crown separated from its shank. Because of the BCQ rod and 25.4-mm (1-in) pipe in the hole, and the fear that the pilot hole would be lost if that pipe were removed, an attempt was made to grind up the bit crown with a milling tool. However, before the mill could reach the bit crown it cut the 25.4-mm (1-in) pipe in two and left a number of pieces of pipe scattered throughout the reamed portion of the hole.

Attempts to fish the 25.4-mm (1-in) pipe were then begun and continued without success until a television camera (fig. 13) was brought in and run in the hole on March 13, 1979. Using the camera it was possible to find the main string of pipe and determine its condition. On the second fishing attempt after sighting the top of the main string of the 25.4-mm (1-in) pipe, the overshot tool latched onto the pipe and both the main string of 25.4-mm (1-in) pipe and all of the BCQ rod in the hole were brought out. Four more days were required to fish shorter sections of 25.4-mm (1-in) pipe from the hole using alternating overshot and camera runs. Finally, when most of the remaining pipe was below the water level in the hole (the camera could not give a usable picture in water because of the suspended solids), a switch was made to grinding the pipe with a mill and fishing the small pieces (fig. 14) with a magnet. The last of the debris was removed from the hole on March 8, 1979. A spear with spring-loaded latches (fig. 15) was used to retrieve the bit crown on March 30, 1979.

This fishing operation cost 26 working days (41 calendar days) and approximately $93,000. The direct and indirect labor costs totaled $49,800 and the costs for fishing tools were $22,600. Had there been no BCQ or 25.4-mm (1-in) pipe in the hole the crown could have been fished directly using the spear, at greatly reduced cost.

Reaming With a Stinger Assembly

Reaming operations were finally resumed on April 4, 1979, using a stinger (figs. 12 and 16) to guide the bit, instead of the pipe string that had been removed while fishing the bit crown. The use of a stinger soon proved to be as effective as, and far safer than, the use of a guide string. No attempt was made to run the guide string again and no problems were encountered in the use of the stingers.

Drilling Summary

The reaming operation was completed on May 9, 1979. The operation took 121 days, of which 40 were off days and 26 were spent in fishing for the bit crown. The average drilling rate was approximately 1 m/h (3.4 ft/h). However, the overall drilling rate when fishing, downtime, and off days are included, drops to less than 0.2 m/h (0.6 ft/h). The average bit cost per meter was $46.90 ($14.90/ft) (table 4).

TABLE 4. - Bit costs--reaming

Bit[1]	Initial cost,[1] dollars	Salvage value, dollars	Net cost, dollars	Depths drilled		Total depth drilled		Cost, dollars	
				m	ft	m	ft	m	ft
Strata-Pax:									
Type 11660, SN-8S55615[2].......	4,215.82	None	4,215.82	0- 83	0- 273	83	273	50.79	15.44
PT 11685, SN-9S42322[3].......	4,750.00	None	4,750.00	189-257	620- 842	[4]68	[4]222	69.85	21.40
SN-9S41252[3]........	[5]0	None	0	187-189	612- 620	2.4	8	NAp	NAp
Diamond:									
Type 147568, SN-8S56468[2].......	9,165.36	3,368.71	5,796.65	83-187	273- 612	103	339	56.28	17.10
Type 20-358-024-S, SN-9S45758[3].......	9,214.06	5,073.26	4,140.80	257-369	842-1,209	112	367	36.97	13.82
Type 20-358-024S, SN-9S46901[3].......	9,343.29	5,073.26	4,270.03	369-494	1,209-1,620	125	411	34.16	12.34
Total or average	36,688.53	13,515.23	23,173.30	NAp	NAp	494	1,620	46.91	14.30

NAp Not applicable.
[1]All bits were acquired in January 1979.
[2]222.25 mm by 63.5 mm (8-3/4 by 2-1/2-in).
[3]219 mm by 63.5 mm (8-5/8 by 2-1/2-in).
[4]Probably damaged by steel in the hole after the fishing job.
[5]No charge because bit came apart in the hole.

FIGURE 12. - Flat-faced Strata-Pax reamer and stinger. Stinger diameter is 63 mm (2-1/2 in).

FIGURE 13. - Television camera. Light source in left foreground.

FIGURE 14. - Debris fished from EM-19. Long pieces were picked up by overshot and small pieces by magnet.

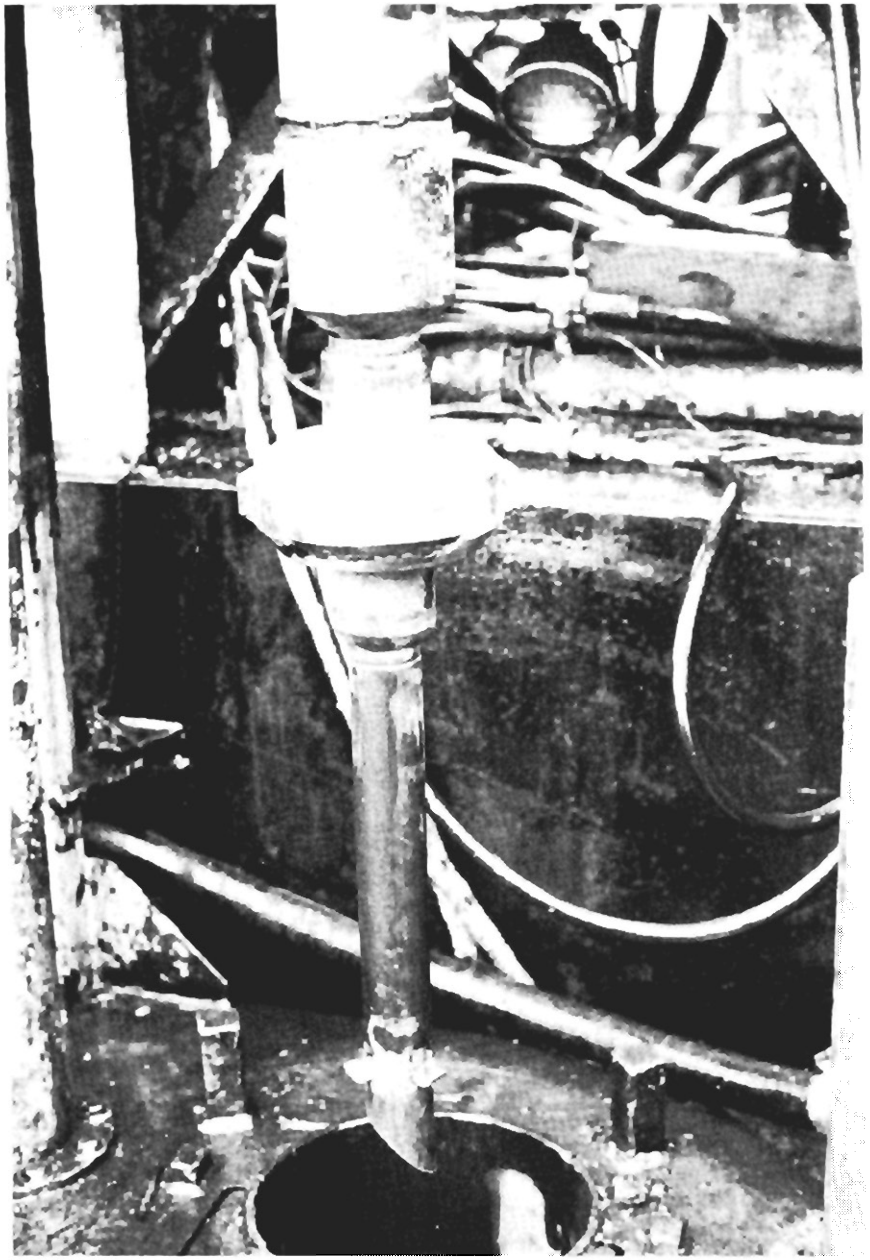

FIGURE 15. - Bit-crown fishing spear. Large ring at the top is a centralizer.

FIGURE 16. - Reaming stinger and diamond reaming bit.

Casing and Cementing

The hole was cased on May 10, 1979, using 486 m (1,595 ft) of 140-mm (5-1/2-in) o.d., K-55 grade, range 2, LT&C casing. The casing ran freely to a depth of 442 m (1,450 ft). Below that point it was necessary to fill the casing with water to reduce its buoyancy, and to use the rig to push the casing to the desired depth. The next-to-last joint of casing required a down pressure of 57,800 N (13,000 lb) and the last joint required a down pressure of 8,900 N (2,000 lb). Fifteen centralizers were also run in the hole, most of them on the bottom 91 m (300 ft), to insure a uniform cement sheath around the pipe in order to provide a good seal.

The cementing operation was completed on May 11, 1979. A total of 9.6 m^3 (340 sacks) of Pozzolan cement were used, with gilsonite added to decrease the cement density and help prevent the lost-circulation zones from taking all of the cement. Good cement returns were obtained at the surface, indicating that the cementing operation was successful. On May 16 the bottom hole plug was drilled out, using a string of 60-mm (2-3/8-in) drill pipe and a rock bit, in preparation for the horizontal drilling.

Horizontal Drilling

Horizontal drilling with the Dyna-Drill was begun on May 17, 1979. It was planned initially to drill just enough hole to drill slightly past the vertical dewatering hole EM-20 (fig. 17). Drilling was then to be suspended and a hydraulic stimulation treatment done on EM-20. The horizontal hole was drilled to 528 m (1,732 ft) MD on May 23, slightly past EM-20. The dewatering hole was stimulated on May 25 with a 70.5-m^3 (21,000-gal) foam treatment containing 11,800 kg (26,000 lb) of 20/40-mesh sand propping agent. This procedure was designed to provide a path for increased flow of water to the vertical dewatering hole EM-20 by providing a direct high-permeability connection between the horizontal holes and EM-20.

Cuttings from the pilot hole drilled in December 1978 and interpretation of the gamma-ray log run at the same time indicated that the directional hole had entered the top of the Pittsburgh coalbed at about 486 m (1,595 ft) MD. This point had therefore been chosen for the bottom of casing. The initial horizontal drilling indicated that the interpretation had been incorrect. It was found necessary to drop vertically through approximately 0.6 m (2 ft) of roof rock to enter the main bench of the coalbed. Reevaluation of the gamma-ray log in light of the additional drilling information indicated that the pilot hole probably had been drilled through the rider coal above the Pittsburgh, into the roof shale directly above the Pittsburgh coalbed and then, instead of entering the Pittsburgh coal the hole either reentered the roof coal or terminated in the shale. Because of the similarity in hardness and color of the shale and coal, the boundary of the roof coal and shale was not even noted at the time by the driller. Even after completion of all of the drilling and close scrutiny of the original gamma-ray log it is difficult to make an interpretation of the exact sequence of rock types drilled.

The error proved to be a major problem for two reasons. First, the vertical dewatering hole and the directional hole had been placed so that fractures from the stimulation treatment of the coalbed done in EM-20 would cross the path of the horizontal holes just beyond the bottom of casing. Since the horizontal hole was probably in shale near the anticipated point of intercept with the stimulation fracture (fig. 17), direct communication may not have been achieved. Figure 17 indicates that the fracture intercepted horizontal hole H1. However, the uncertainty in the position of EM-19 with respect to EM-20 is sufficient that the fracture could easily have crossed the hole where the hole is in rock. Indeed, no sand was ever seen in the cuttings

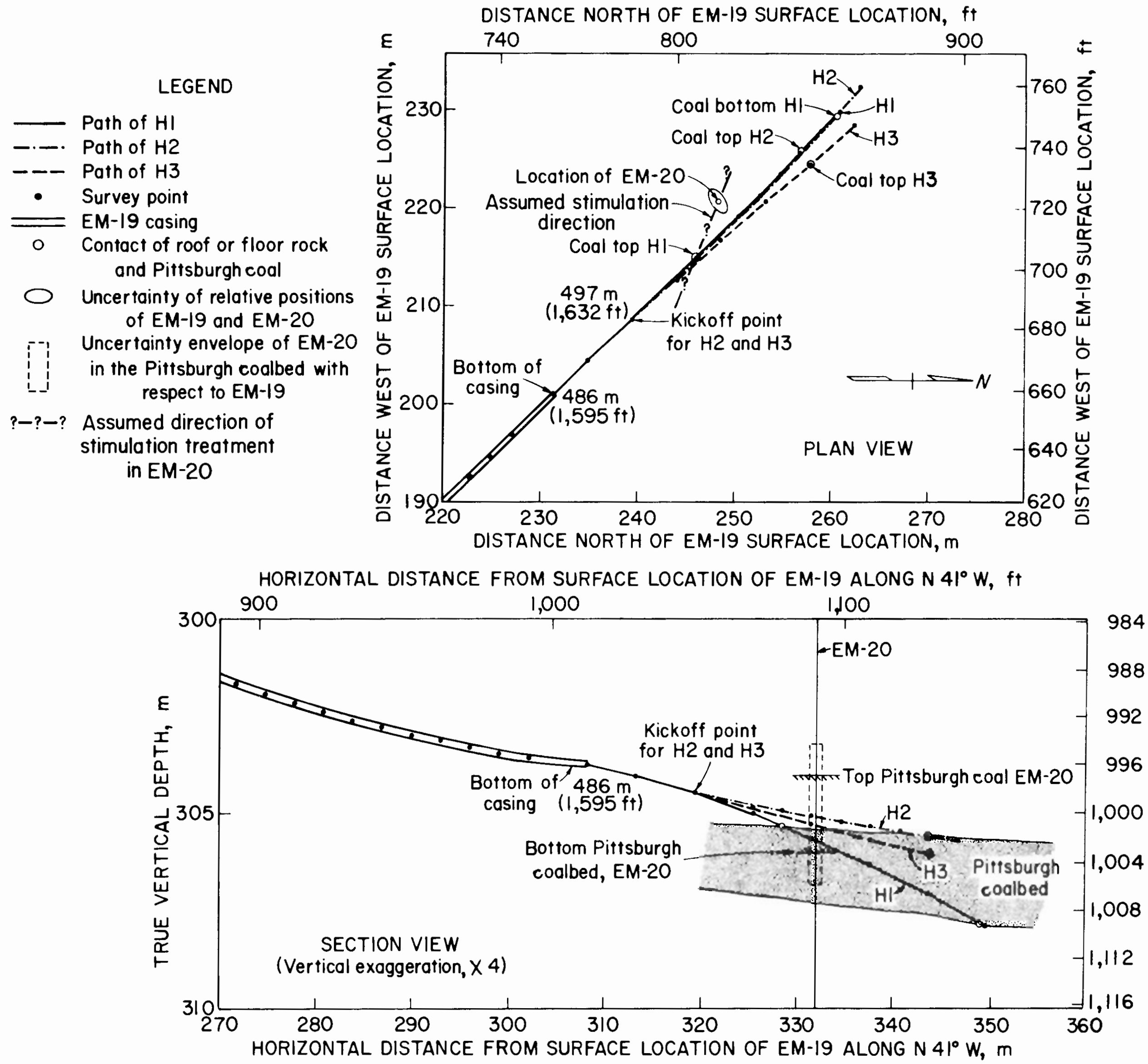

FIGURE 17. - Plan and section views of geometry of EM-19 near the bottom of casing. EM-20 location also shown.

from the directional hole. Secondly, this meant that the initial portion of each horizontal hole was in rock which had a tendency to cave or slough, resulting in plugging of the holes. The best method of insuring that the casing reaches the target coalbed in future directional holes would be to continue the pilot hole after reaching the horizontal, and to then drill steeply downward until the bottom of the coalbed is reached. This portion of the hole would confirm the well position and would then be abandoned during the reaming and casing operations.

Horizontal Hole H1

Continuous drilling of the first horizontal leg H1 (fig. 18) was begun on May 29, 1979. Clear water was used as the drilling fluid to eliminate any risk of mud additives plugging the coalbed fracture system. However, the use of clear water led to three problems. The first and most important was that the low viscosity of water made removal of drill cuttings from the hole more difficult. The problem was made more acute by the low flow rates required by the

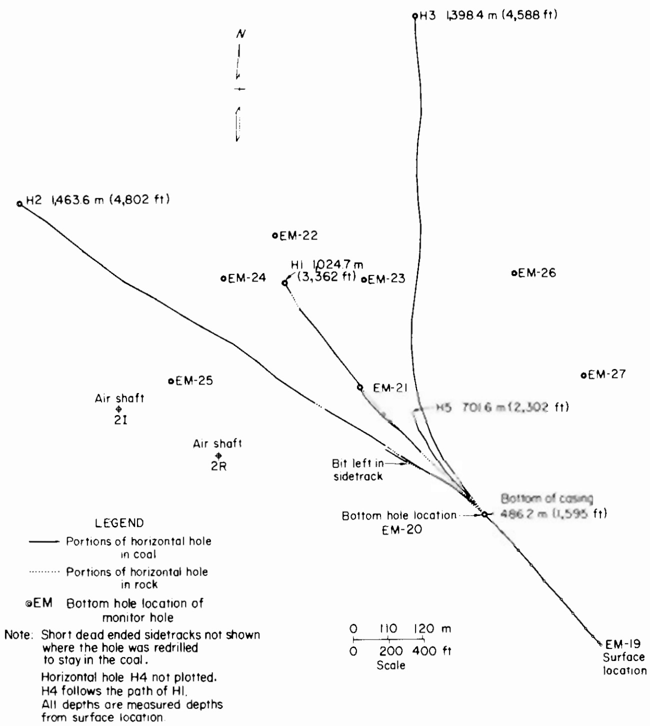

FIGURE 18. - Plan view of horizontal holes and bottom hole locations of monitor holes.

Dyna-Drill. The flow rates were increased from 5.5 to 9.0 m^3/h (24-40 gal/min) and eventually to as high as 13.6 m^3/h (60 gal/min). This increase in flow rate eventually led to problems with Dyna-Drill tool life.

A second problem encountered when using clear water was fluid loss. This problem essentially could not be solved without the risk of damaging the coalbed's natural fracture permeability and decreasing future methane gas flow rates. Fluid losses as high as 57 m^3/d (15,000 gal/d) were experienced before H1 was completed, and remained at that rate while holes H2 and H3 were drilled.

The third problem was the risk of the fresh water causing sloughing of water sensitive clays in the shales, located directly above the coalbed, which were occasionally drilled through. This problem did not become apparent immediately, but eventually became very serious.

One drilling problem encountered that had been anticipated, was the problem of keeping the hole in the coalbed and controlling the hole path. It was decided early in the drilling operation that sidetracks were to be avoided, if possible, since it was felt that it would be difficult to reenter the proper hole after the drilling assembly had been removed from the hole for any reason. It was also assumed that sidetracking would take too much time. When the hole deviated from the main coalbed, every attempt was made to reenter the coal without backing up and sidetracking (starting a new hole, leaving part of the original hole as a side branch). Since the directional control engineer was still learning how to control the drilling assembly, and because it was difficult to predict the dip of the coalbed, large sections of hole H1 were drilled in rock (fig. 18 and table 5). One sidetrack was attempted on hole H1 because a large section was drilled completely in rock between 685.2 and 801.6 m (2,248-2,630 ft) MD. The hole was successfully sidetracked in coal at 674.2 m (2,212 ft) MD and was drilled to 976.6 m (3,204 ft) MD with only two short sections totaling 8.5 m (28 ft) in rock.

TABLE 5. - Horizontal distances drilled

Hole	Total depth from surface		Horizontal length, casing to total depth		Hole in coal, including sidetracks		Hole in rock, including sidetracks	
	m	ft	m	ft	m	ft	m	ft
H1.........	1,024.7	3,362	538.6	1,767	413.0	1,355	253.0	830
H2.........	1,463.4	4,802	977.5	3,207	1,018.6	3,342	180.7	593
H3.........	1,398.4	4,588	912.3	2,993	915.0	3,002	73.5	241
H4.........	751.3	2,465	265.2	870	157.6	517	95.1	312
H5.........	701.6	2,302	215.5	707	180.4	592	29.9	98
Total...	NAp	NAp	2,909.0	9,544	2,684.7	8,808	632.2	2,074

NAp Not applicable.

NOTE.--Total all drilling, 3,311 m (10,882 ft).

The drilling assembly used to drill H1, and later holes H2 and H3, was the same one used to drill the pilot hole (fig. 7). In horizontal drilling, however, the emphasis is on maintaining hole angle against the force of gravity, without building angle. One attempt was made to use the 0.0087-rad (30-min) bent housing to maintain angle, but it was found inadequate during the occasional periods when rapid building of angle was required. The 0.013-rad (45-min) bent housing was then tried and became the standard assembly for drilling the horizontal holes. The 0.013-rad (45-min) housing could actually build angle at a greater rate than usually required. Since its additional build capacity could not be "turned off," a technique was developed by the directional drilling engineer to render this capacity relatively harmless when not needed and available when required without making pipe trips to change housings. This was done by rotating the "tool face," the plane of the bend, to some angle, typically about 0.79 rad (45°) either right or left of vertical. This rotation would be held either right or left as required for about 100 m (330 ft) and then the tool face would be turned the other way. This resulted in a smooth, sinuous hole path, as seen in plan view (fig. 18). The additional curvature did not increase pipe friction much because it was done in a smooth and gradual manner. The hole projection was followed by having the curves repeatedly cross left and right of the desired path.

Hole H1 was initially surveyed after each 3.3-m (10- ft) pipe joint was drilled. As the directional drilling engineer gained experience and information on the coalbed, the interval was increased to two joints, except at critical points. Because of the uncertainty in control techniques and the lack of information on the coalbed structure, about 38% of the total of 666 m (2,185 ft) of horizontal hole H1 was drilled in rock.

A total of 15 full and 2 partial pipe trips were made while drilling H1, 10 of which were required to retrieve the survey tool after it had hung up in the drill pipe and caused the wireline to break. This was a serious problem while H1 was being drilled, but better equipment eventually solved the difficulty. Three trips were also made because of Dyna-Drill failures, and one trip each due to a plugged bit, a change of bent housings, a parted BQ rod, and a weekend shutdown.

H1 was terminated prematurely on July 13, 1979, at 1,024.7 m (3,362 ft) MD when it was found to be impossible to reenter the hole after a pipe trip. The hole had reached a total horizontal distance of 538.6 m (1,767 ft) (table 5) beyond the end of casing and was drilled in 26 working days, an average of 20.4 m (67 ft) per day. Before the leg was terminated it had become apparent that many improvements would be required to obtain acceptable daily drilling rates.

Horizontal Hole H2

Leg H2 was begun on July 16, 1979, and about one-half of its total length was completed before the necessary changes in drilling technique could be developed and put to use. The first action taken was a meeting with Dyna-Drill engineers to discuss the problems of tool life and reliability. Two changes were made after this meeting. The flow rates through the Dyna-Drill were reduced in an attempt to decrease stresses on the tools, increase tool life, and reduce the number of pipe trips required for tool repair. (At measured depths of 1,000 m (3,300 ft) a pipe trip could take as long as 16 hours.) The second change was made to offset the effects of lower flow rates on cuttings removal, by the addition of Con-Det, a concentrated detergent, to the drilling fluid. The Con-Det acted to help remove cuttings, but presumably did not plug off the coalbed fracture system. Evidence that this was the case came from several of the vertical monitoring holes where, after long periods of stability the surface pressures measured in the monitor holes increased shortly after use of the Con-Det was begun. This was probably due to an increase in permeability in the horizontal holes themselves when the fine cuttings were removed. Eventually an experimental partial bypass valve (fig. 7) just above the Dyna-Drill tool was also used which allowed high flow rates in the hole, but allowed only flows of 5.5 m^3/h (24 gal/min) through the tool. The rest of the flow bypassed the Dyna-Drill by way of the valve.

The problems associated with drilling in rock (primarily hole caving, but also sticking of drill pipe) were eliminated when it was discovered that it was easier to back up and sidetrack immediately after leaving the coal (fig. 19B) than to try to gradually guide the well path back into the coal (fig. 19A). Eventually sidetracks could be accomplished in as little as 3 hours with no problems in reentering the proper hole. The acceptance of more sidetracks also made staying in the coalbed less critical. This allowed an increase in drilling rates and an increase in

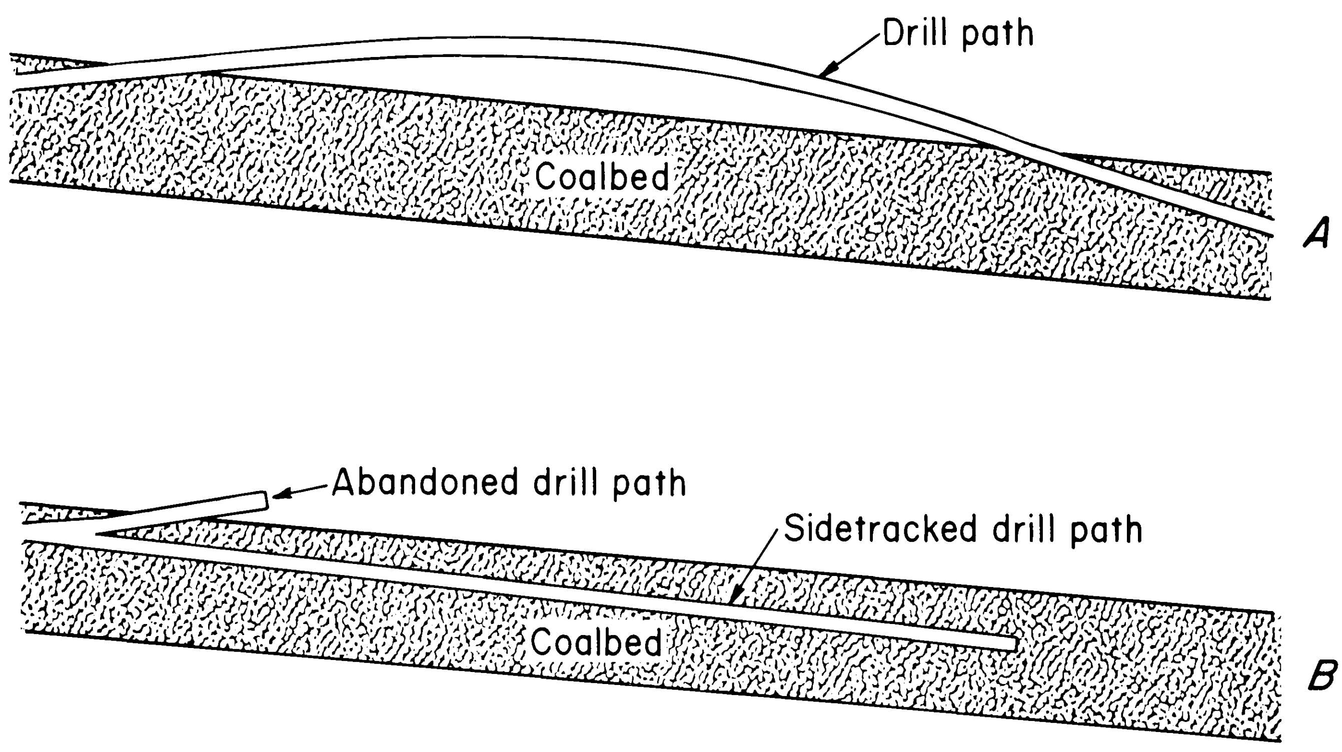

FIGURE 19. - Two methods of following the coalbed. Method B is recommended.

surveying intervals from every one or two joints of pipe to every two to four joints. Since it took about 1 hour for an average survey and only 20 to 40 minutes to drill two joints (6.6 m or 20 ft) the time saving was significant, an increase of about 40% in the drilling rate.

Leg H2 (fig. 18 and table 5) was completed on August 31, 1979, at a total measured depth of 1,463.4 m (4,802 ft). Of the total horizontal distance drilled, 1,199.3 m (3,935 ft), only 15% was in rock, a great improvement over the results of H1. The maximum horizontal distance reached from the bottom of casing was 977.5 m (3,207 ft) which made it the longest horizontal hole drilled in EM-19. H2 was drilled with a total of five sidetracks, which took up 221.8 m (728 ft) of the total distance drilled. One of these sidetracks was required when a broken drive shaft in the Dyna-Drill caused a bit to be left in the hole. When fishing failed to remove the bit this hole had to be abandoned and sidetracked.

A total of 16 pipe trips were made in H2, 11 because of Dyna-Drill failures, and one each caused by a survey pumpdown tool failure, a drill rod parting, a bit change, a bent housing change, and the completion of the hole. The average daily footage was 27.1 m (89 ft) indicating that the improvements in drilling methods, although introduced about half way through the drilling of H2, had begun to have a positive effect.

Horizontal Hole H3

All of the successful techniques developed while drilling H1 and H2 were used in drilling leg H3, except the use of the bypass valve which had been sent in for repairs when H3 was started. H3 was begun on September 4, 1979. On September 21, 1979, the Dyna-Drill was finally pulled out of the hole after drilling all of H3 in a single run of 226 drilling hours. The hole had been drilled to a measured depth of 1,398.4 m (4,588 ft), a horizontal distance of 918.3 m (2,993 ft) from the end of casing (fig. 18 and table 5). The average distance drilled per working day (14 days) was over 64.9 m (213 ft). The hole was sidetracked eight times for an average of 114 m (374 ft) between sidetracks. Only about 7.5% of the total length of hole drilled was in rock and beyond a measured depth of 522 m (1,712 ft) the hole was continually in coal, except for short "dead ends" in rock which were bypassed each time the hole was sidetracked. Leg H3 was also terminated prematurely because it could not be reentered due to apparent sloughing of the shale section at the bottom of casing. If the hole could have been reentered, there is every reason to believe that it could have been extended a substantially greater distance.

Horizontal Holes H4 and H5

After September 21, 1979, several unsuccessful attempts were made to reenter the horizontal holes and as part of these attempts two additional holes, H4 and H5, were drilled. H4 essentially followed the path of H1 and H5 was drilled between H1 and H3.

Reaming Horizontal Sump

The final drilling operation performed on the directional hole was the reaming of a 45-m (147-ft) long horizontal sump, 216 mm (8-1/2-in) in diameter from the bottom of casing to a measured depth of 531 m (1,742 ft). The exact path of this sump was not surveyed, but it is assumed to have followed the path of H2, since it entered the coal at 522 m (1,712 ft) MD, the same depth that H2 entered the coal. This underreaming took approximately 2 days, most of which was spent in running and pulling the 121-mm (4-3/4-in) diameter tricone bit and the 216-mm (8-1/2-in) diameter casing underreamer (fig. 20) used to open the hole. The operation was completed on October 9, 1979. The sump was drilled partly as a gathering area for water and partly to help keep a path open through the roof shales which had already shown themselves to be major problems.

FIGURE 20. - Casing underreamer. Open diameter, 216-mm (8-1/2-in); closed diameter, 121-mm (4-3/4-in).

Completion Work and Initial Production Rates

Work was begun on October 9, 1979, to equip the vertical dewatering hole, EM-20, to dewater the coalbed, and to equip it and the directional hole for gas production (fig. 21). EM-20 (fig. 22) was put on water production using a downhole plunger pump on November 15. Water production began at the pump's capacity of 20.3 m^3/d (128 bbl/d) but declined rapidly. The initial gas flows ranged up to 34 m^3/d (1,200 ft^3/d) (fig. 23), but no increase in gas production was seen as the water production dropped. At the same time pressures in the coalbed, read from the vertical monitor holes, initially dropped rapidly and then leveled off. It was believed that either barrier to water flow between EM-20 and the directional hole, EM-19, caused by caving of the horizontal holes where they had been drilled in roof rock at the bottom of

FIGURE 21. - EM-19 surface installation. Wellhead and pump control panel at left.

casing or the plugging of the induced fractures from the stimulation treatment were directly responsible. During the period December 1979 through February 1980, several attempts were made to increase water production by flushing out both EM-20 and EM-19 with water in the hope of cleaning out material that might be blocking the fracture system and the holes. Attempts were also made to open up the fracture originally created in EM-20 by pumping in water at pressures well above those required to induce the original fracture. The indications are that these procedures did not accomplish the desired results and may have caused harm by accelerating the caving of shales at the bottom of casing in EM-19.

Tests conducted in EM-19 in January 1980, using compressed air to remove water from the hole, showed that water production rates as high as 31 to 48 m^3/d (220-300 bbl/d) could be sustained for a week or longer. During these tests, gas flows of up to 2,500 m^3/d (90,000 ft^3/d) were seen for brief periods after the air compressor was shut off, and shortly before the increasing pressure of the water column in the hole prevented further gas flow.

In February 1980, water level measurements were made in EM-19 which indicated a bottom hole pressure of 1,280 kPa (186 lb/in^2g), while at the same time the pressure in EM-20 was atmospheric. Since

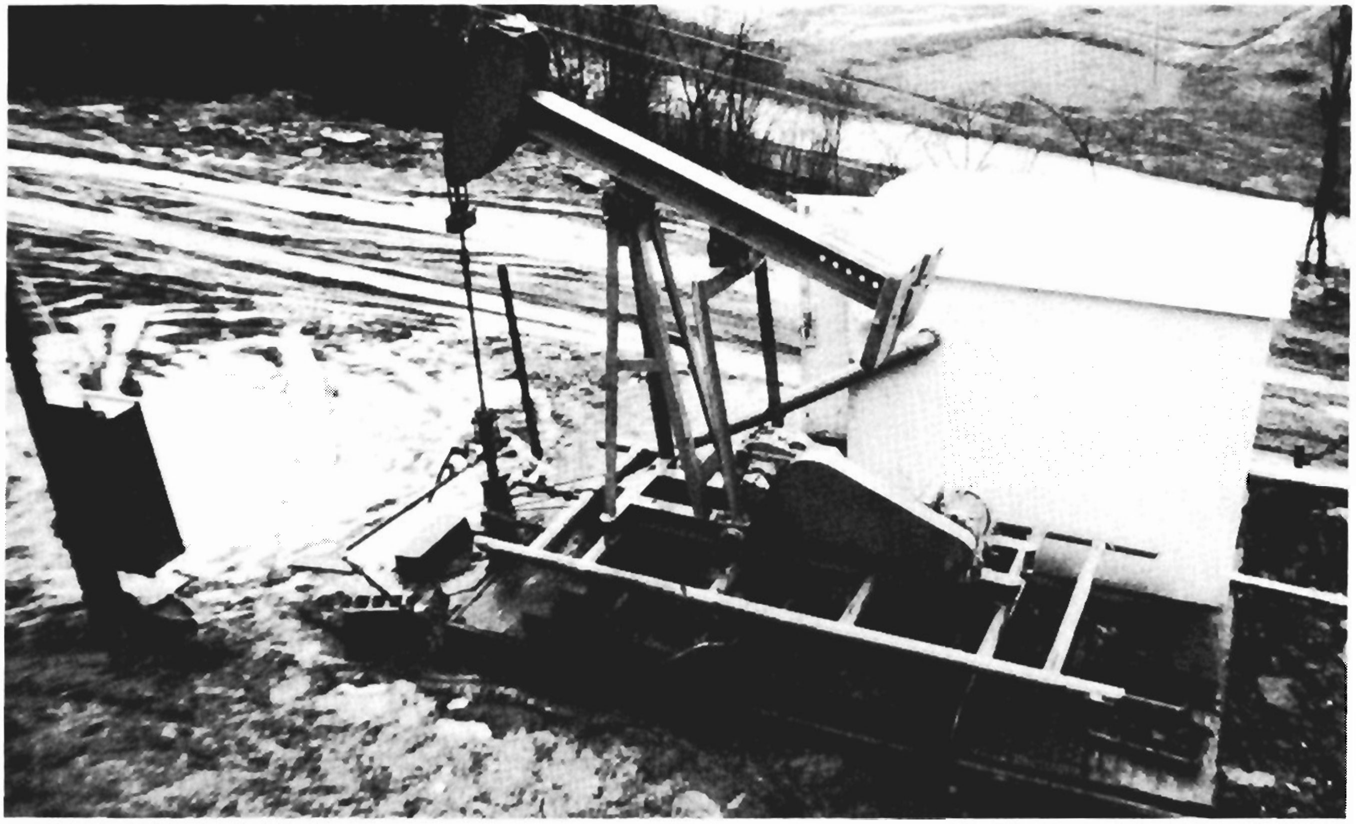

FIGURE 22. - Dewatering hole EM-20.

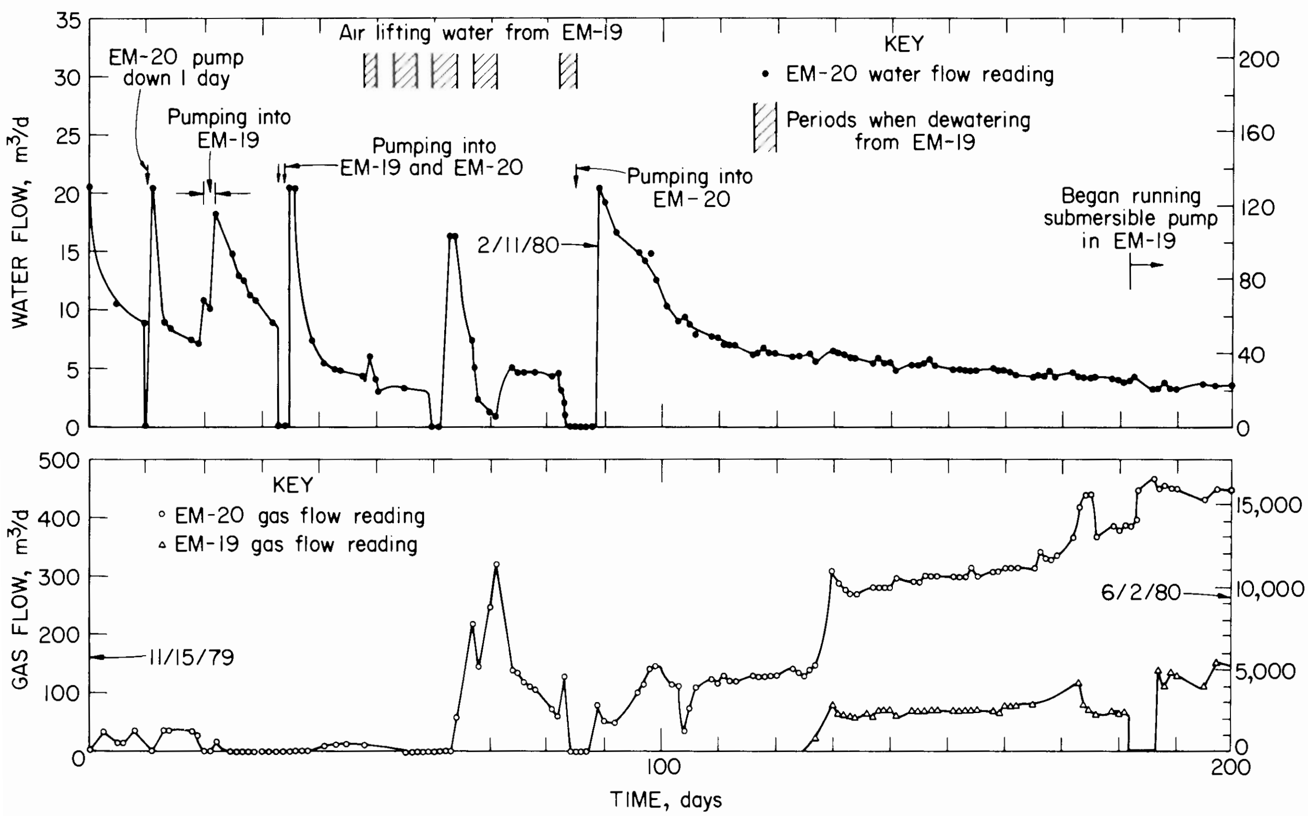

FIGURE 23. - Production data from EM-19 and EM-20.

the distance between EM-20 and EM-19 was about 6 m (20 ft), this indicated a high pressure gradient between the holes. These facts confirmed the assumption made in November-December 1979 that the permeability of the coalbed between EM-19 and EM-20 was not sufficient to allow drainage of the water produced from the horizontal holes, by way of EM-20. It also indicated that the permeability of EM-19 to gas and water flow was high. Therefore, it was decided in late-February to install a water pump in EM-19.

In March 1980, an electric submersible pump was ordered for use in the directional hole. The pump was not available until late-April 1980. During this period, gas flow from EM-20 (fig. 23) gradually increased from 37 m^3/d (1,310 ft^3/d) to 340 m^3/d (12,000 ft^3/d) and water flow decreased from 9.3 m^3/d (59 bbl/d) to 4.7 m^3/d (30 bbl/d). Gas began to flow from EM-19 in March and increased to 79 m^3/d (2,800 ft^3/d) (appendix B).

After some minor installation difficulties the submersible pump was installed at a measured depth of 485 m (1,590 ft) and put into operation in mid-May. The pump was a 95-mm (3.75-in) diameter, 75-stage centrifugal type unit with bronze impellers, capable of lifting 1.0 m^3/h (7 gal/min) against a waterhead of 450 m (1,500 ft). The pump was powered by a 440-V, three-phase, 3.73-kW (5-hp) motor (fig. 24). An undercurrent relay was installed in the surface control panel to prevent the pump from being damaged when the hole had been pumped down. This relay worked by turning the pump off when the current in one phase dropped below a preset minimum (about 80% of the motor full load rating). When the water level dropped to the level of the pump intake the impellers began working against gas, which took less effort, and

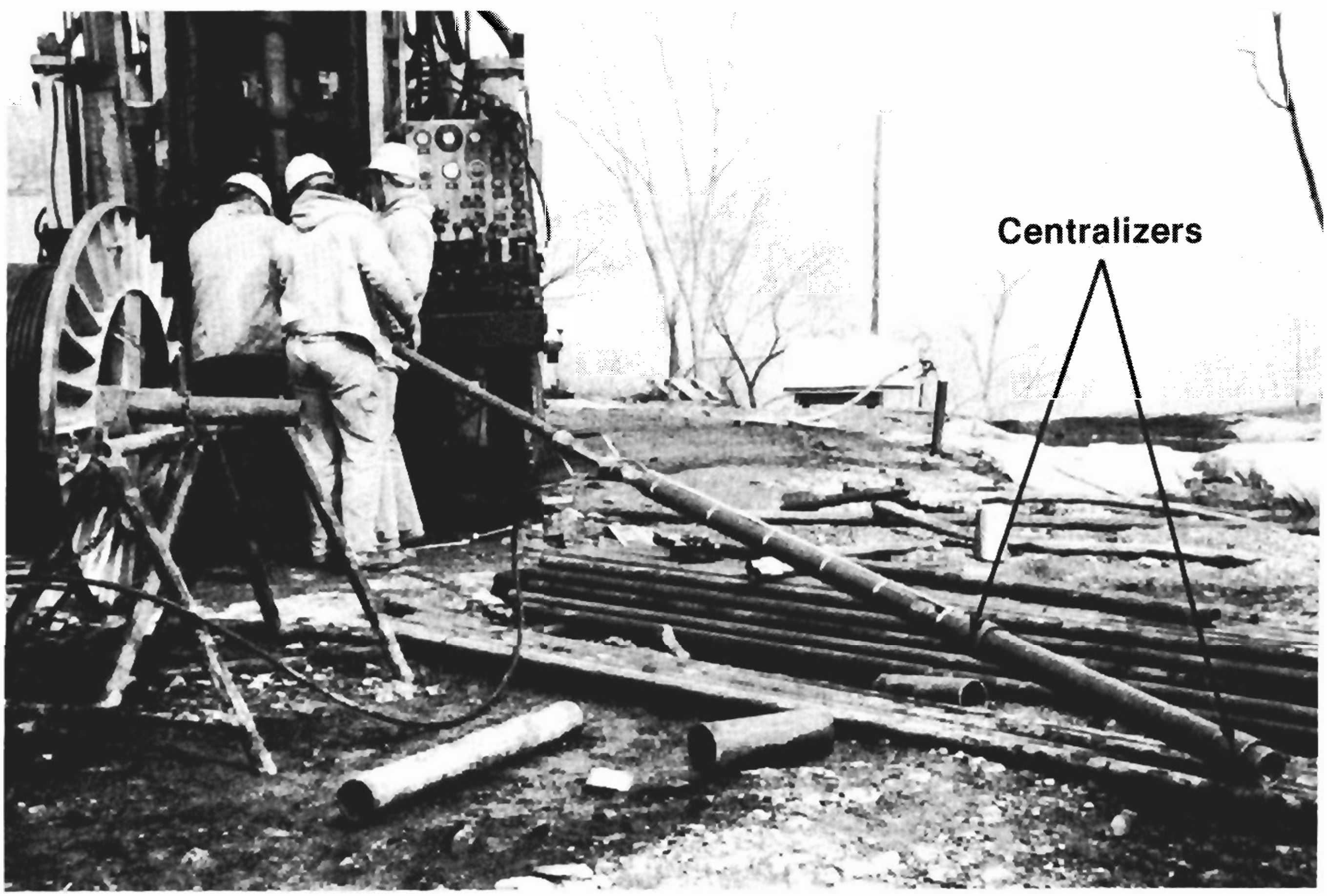

FIGURE 24. - Crew running the submersible pump into EM-19. Note centralizers for motor at right.

the current then dropped below the undercurrent rating. The pump was then shut off and was restarted later by an adjustable timer in the control panel.

Within a short time it became obvious that there were problems with this arrangement. The first time the pump was started it operated only 30 minutes and it then shut off. It was assumed that there was sufficient water for the pump and that, therefore, gas entry was activating the undercurrent relay prematurely. To eliminate this problem a pump shroud was designed to prevent entry of gas to the pump. As of late 1980, this shroud had not yet been tested. In the meantime, adjustments to the timer and to the undercurrent relay, made over a period of several months, eventually allowed the pump to pump the well down. The water production in EM-19 was never higher than 1.6 m^3/d (10 bbl/d) and was usually much less. The low water levels in the well were also verified by the use of a sonic well sounding device. These results, along with the January 1980 water production data, indicated that caving in the roof rock just below casing was becoming progressively worse and that some remedial action was required if acceptable gas flow rates were to be obtained from the directional hole system. Physical evidence for the caving of the roof rock was also available in the form of pieces of coal and shale airlifted from the hole in January 1980 (fig. 25).

FIGURE 25. - Shale and coal blown out of EM-19, January 1980. Pen cap 57 mm (2.25 in) long. Note large cement piece.

In May 1980, work was begun to design equipment to redrill the hole from the bottom of casing in EM-19, through the roof shale and well into the Pittsburgh coalbed. A plastic liner casing will be installed in this hole to control further caving of the roof shales and to create a permanent path for water and gas movement from the horizontal holes H1, H2, and H3 into the casing of the directional hole.

PROJECT COSTS

Detailed Cost Analysis

Table 6 shows the costs for the directional hole, EM-19, broken down by major expenditure items. The total costs column shows the actual total of all of the invoices received from the contractor. The project startup column gives the costs of maintaining key personnel from September 1977 to August 1978, while the cooperating coal company searched for an alternate drilling site. The original site became unavailable at about the same time as the drilling contract was signed. The fishing costs column gives the costs of the February-March 1979 bit-crown fishing job during the reaming operation. The end-of-project column gives the breakdown of the costs at the end of the project between November 1979 and May 1980 to put the system on production and to maintain a capability to perform service and remedial work. In the last column, the total EM-19 costs, minus the nondrilling and major fishing costs have been computed.

The net costs in table 6 give an estimate for the cost of the directional hole at 1979 prices ($1,169,530.58) assuming that no unanticipated expenditures such as those identified had been encountered. The cost of the vertical dewatering hole, the monitoring holes, and the corehole are also not included. Nor are costs for drill rig and mud pump rental since these were Government owned. Also, the costs of site preparation are not included because they were paid by the Emerald Mines Corp.

TABLE 6. - Directional hole (EM-19) drilling costs

(1979 dollars)

	Total costs	Project startup costs	Fishing costs (reaming)	End-of-project costs	Net cost[1]
DIRECT					
Labor:					
Nonsupervisory	195,800.39	0	16,587.60	27,667.38	151,545.41
Supervisory	146,349.15	22,100.00	6,560.00	24,793.53	92,895.62
Total	342,149.54	22,100.00	23,147.60	52,460.91	244,441.03
Drilling:					
Geolograph	10,425.69	0	1,171.37	0	9,254.32
Directional control equipment	10,929.30	0	0	0	10,929.30
Directional drilling engineer	66,750.00	0	0	0	66,750.00
Dyna-Drill	82,685.29	0	0	0	82,685.29
Bits and subs	40,707.74	0	0	0	40,707.74
Drill pipe	52,759.83	0	3,690.00	0	49,069.83
Mud	93,089.38	0	834.44	0	92,254.94
Mud pumps, repair and parts	18,778.45	0	571.95	0	18,206.50
Fishing tools	30,232.27	0	22,591.92	0	7,640.35
Plugback cementing	1,155.87	0	0	0	1,155.87
Logging	1,100.00	0	0	0	1,100.00
Fuel and oil	33,776.09	0	1,900.00	2,793.45	29,082.64
Labor bond	5,127.00	0	341.80	0	4,785.20
Total	447,516.91	0	31,101.48	2,793.45	413,621.98
Completion:					
Casing	12,604.73	0	829.00	0	11,775.73
Cementing	5,304.81	0	0	0	5,304.81
Wellhead equipment	2,413.42	0	0	0	2,413.42
Surface equipment and meter house	6,116.05	0	0	0	6,116.05
Downhole completion equipment	8,950.55	0	0	0	8,950.55
Total	35,389.56	0	829.00	0	34,560.56
Labor overhead (1.1514 × total labor)	392,895.28	25,445.94	26,652.15	60,403.49	280,393.70
Subtotal direct	1,217,951.29	47,545.94	81,730.23	115,657.85	973,017.27
Fixed fee (7% of subtotal direct)[2]	85,162.29	3,328.22	5,721.12	8,096.05	68,016.90
Total direct	1,303,113.58	50,874.16	87,451.35	123,753.90	1,041,034.17
INDIRECT					
Plant costs:					
Pickup and car rental	17,534.00	2,805.00	902.00	3,300.00	10,527.00
Trailer rental	5,942.89	0	398.52	524.70	5,019.67
Equipment repair and maintenance	30,980.20	0	2,020.00	0	28,960.20
Water and tanks	44,616.00	0	280.53	500.00	43,835.47
Telephone	5,090.36	0	384.62	757.12	3,948.62
Sanitation and safety equipment	5,720.75	0	72.16	528.15	5,120.44
Miscellaneous supplies and small tools	9,911.95	0	640.00	0	9,271.95
Hauling and shipping	9,965.15	0	245.00	1,820.00	7,900.15
Per diem	3,951.00	0	231.00	801.00	2,919.00
Electrical work	3,191.47	0	0	0	3,191.47
Total	136,903.77	2,805.00	5,173.83	8,230.97	120,693.97
Fixed fee (7% of total plant costs)[2]	8,937.13	196.35	362.17	576.17	7,802.44
Total indirect	145,840.90	3,001.35	5,536.00	8,807.14	128,496.41
Grand total	1,448,954.48	53,875.51	92,987.35	132,561.04	1,169,530.58

[1]Excludes startup, fishing, and end-of-project costs.
[2]Up to a contract maximum of $119,713.00.

Table 7 shows an estimated cost for each of the five major drilling operations performed on EM-19. These costs were determined from the contractor's monthly invoices, which did not indicate the exact purpose of each item purchased. This means that each individual invoice had to be studied to determine the purpose of the items purchased and allow assignment of the cost to a particular operation. The care required to do this was exercised in the case of labor and such large and identifiable expenditures as the purchase of bits, water, mud, and directional drilling equipment. However, where the purpose of an item was more difficult to determine (such as small tools and miscellaneous items), the costs have been assigned by time period. This means that the cost estimates of table 7 are not exact. However, they should be within 10% of the actual costs. The cost estimated for the pilot hole drilling has been adjusted to remove the costs incurred during a period of 5 days when the rig engine broke down. However, no changes have been made to correct for the expenses and lost time caused by lost-circulation problems (appendix A gives the hours lost from this cause). Similarly the only costs removed from the estimate for the reaming are those for the bit crown fishing operation shown in the fishing costs column of table 6. Since the total fixed operating cost of the project (including fixed plant costs, labor, labor overhead, fixed fees, directional drilling equipment, and the directional driller's time) for a single working day was about $3,400 ($2,400 when reaming), even minor improvements could have a significant affect on the drilling cost. The change in the per meter costs of horizontal holes H1, H2, and H3 reflects the improvements made in drilling technique during the project. The costs of H3 also reflect an extraordinarily long run of a Dyna-Drill tool. But it should be possible to maintain on a production basis a per meter horizontal drilling cost in the range of $100 to $115 ($30-$35/ft).

TABLE 7. - Costs for EM-19 drilling operations

Drilling operation	Estimated cost	Distance drilled		Cost	
		m	ft	m	ft
Pilot Hole[1]	$210,000	504	1,652	$417	$127
Reaming[2]...	330,000	491	1,612	672	205
H1.........	120,000	539	1,767	223	68
H2.........	150,000	977	3,207	154	47
H3.........	70,000	912	2,993	77	23

[1]Cost of 5 days lost time due to rig engine breakdown not included.
[2]Bit crown fishing costs not included.

Project Cost Summary

The total cost of the Emerald Mine directional drilling contract (from September 1977 through May 1980) was $1,814,863.09 (table 8). The vertical dewatering hole cost $136,000.36. This includes the cost of drilling, casing, logging, jet slotting, hydraulic stimulation, and completion of the well for gas and water production. It does not include the cost of the pumping unit and the sucker rods that were obtained as surplus from another Government project. Drilling and completing the seven monitoring holes with water level sensing equipment cost a total of $217,877.23. The corehole drilled at the beginning of the project to determine the coal thickness and elevation cost $12,031.02.

TABLE 8. - Project cost totals

Corehole..................	$12,031.02
Dewater hole (EM-20).......	136,000.36
Monitor holes (EM-21-27)...	217,877.23
Directional hole (EM-19)...	1,448,954.48
Total.................	1,814,863.09

Estimated Costs for a Production Directional Hole

In order to arrive at a reasonable cost estimate for drilling directional hole similar to EM-19, on a production basis, utilizing all of the improved techniques developed during the project, both a time and a cost estimate (in 1979 dollars) have been developed. Table 9 gives a time estimate for a directional hole exactly like EM-19, assuming 1979 costs, no major fishing operations or unusual lost-circulation problems, and assuming that the best equipment and techniques developed while drilling EM-19 are to be used. Table 10 gives the cost estimate for this hole with the additional assumption that the drilling rig and the mud pumps are to be rented for the project. If those items of equipment were purchased and used to drill other vertical and directional wells then their purchase costs could be amortized over several wells reducing the estimated cost for a single project. Based upon these estimates, a directional well exactly like EM-19 could have been drilled and completed for slightly less than $1,000,000.

TABLE 9. - Production hole time estimate[1]

Task	Days
Mobilization and equipment set-up	5
Pilot hole	25
Reaming[2]	40
Casing and cementing	4
Drilling out plug	2
Horizontal drilling:	
H1, 486 to 1,025 m (46 m/d)	12
H2, 498 to 1,464 m (43 m/d)	23
H3, 498 to 1,398 m (43 m/d)	22
Underreaming	4
Well completion	10
Demobilization	5
Total working days	152
Off days	61
Grand total	213

[1]Based upon a 24-hour day, 5 days per week.
[2]Includes time to run and cement intermediate casing.

TABLE 10. - Production hole cost estimate

(1979 dollars)

	Daily cost	Days	Total cost
DIRECT			
Labor:			
Nonsupervisory[1]	743.94	152	113,078.88
Supervisory	224.21	152	34,079.92
Total	968.15	152	147,158.80
Drilling:			
Geolograph	28.50	185	5,272.50
Directional control equipment	76.00	82	6,232.00
Directional drilling engineer	365.00	115	41,975.00
Dyna-Drill	620.00	82	50,840.00
Rig rental	1,000.00	200	200,000.00
Drill pipe,[2] bits and subs	NAp	NAp	75,000.00
Mud	NAp	NAp	50,000.00
Mud pumps, repair and parts	240.00	185	44,400.00
Fishing tools	NAp	NAp	5,000.00
Plugback cementing	NAp	NAp	0
Logging	NAp	NAp	1,100.00
Fuel and oil	90.00	152	13,680.00
Labor bond	NAp	NAp	3,851.00
Total	NAp	NAp	497,350.50
Completion:			
Casing[3]	NAp	NAp	14,975.00
Cementing[4]	NAp	NAp	7,500.00
Wellhead equipment	NAp	NAp	2,413.42
Surface equipment and meter house	NAp	NAp	6,116.05
Downhole completion equipment[5]	NAp	NAp	8,950.55
Total	NAp	NAp	39,955.02
Labor overhead (1.1514 × total labor)	1,114.73	152	169,438.64
Subtotal direct	NAp	NAp	853,902.96
Fixed fee (7% of subtotal direct)	NAp	NAp	59,773.21
Total direct	NAp	NAp	913,676.17
INDIRECT			
Plant costs:			
Pickup and car rental	22.00	213	4,686.00
Trailer rental	9.72	213	2,070.36
Equipment repair and maintenance	50.00	213	10,650.00
Water and tanks	NAp	NAp	12,000.00
Telephone	8.00	213	1,704.00
Sanitation and safety equipment	9.00	213	1,917.00
Miscellaneous supplies and small tools	16.00	213	3,408.00
Hauling and shipping	NAp	NAp	3,500.00
Per diem (rig superintendent)	9.00	152	1,368.00
Electrical work	NAp	NAp	3,191.47
Total	NAp	NAp	44,494.83
Fixed fee (7% of total plant costs)	NAp	NAp	3,114.64
Total indirect	NAp	NAp	47,609.47
Grand total	NAp	NAp	961,285.64

NAp Not applicable.

[1]Based upon a 24-hour, 3-shift day, 5 days per week (one driller and two helpers).

[2]Rental of reaming pipe and purchase of 800 m of BQ wireline rod.

[3]Includes 130 m of intermediate casing not used in EM-19.

[4]Includes cost of cementing intermediate casing.

[5]Primarily cost of submersible pump and cable, but not tubing.

CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions can be drawn from the Emerald Mine directional drilling project. It is technically feasible, with good directional control personnel, to quickly drill a directional pilot hole to a target coalbed. Thirty 24-hour days were required to drill the Emerald Mine pilot hole and approximately 12 days of downtime are included in this period.

Once a target coalbed has been successfully intercepted, it is technically feasible to drill long horizontal methane drainage holes, and keep the holes in the coalbed. As experience was gained in directional control, it was possible to increase the horizontal drilling rate from 20.4 m (67 ft) per day to 64.9 m (213 ft) per day. At the same time, the portion of the hole in coal increased from 62% to 92%. The longest horizontal hole drilled on the project (H2, fig. 1) reached a distance of 977.5 m (3,207 ft) from the end of casing. Based on the drilling experience at the Emerald Mine, it is believed that a horizontal hole could have been drilled significantly beyond the 977.5-m (3,207 ft) distance reached on H2. The only impediment to drilling longer distances was the problem of caving of the holes drilled in shale near the bottom of casing, which prevented reentering the holes.

It is still impossible to determine whether a directional hole is an economical method of draining methane from coalbeds since, as of late 1980, problems specific only to EM-19 have prevented the well from producing gas at what is believed to be its full potential. Once the remedial work has been done and gas production data has been obtained additional analyses will be made.

The most important fact learned about horizontal and pilot hole drilling is that it is vital to confirm that the hole really is in the target coalbed. The accuracy of current well surveying equipment is at best ±0.6 m (2-3 ft) vertically at the measured depth of EM-19, and many coalbeds are in the range of 1 to 3 m (3-10 ft) in thickness. In addition, experience with survey data from several directional holes (the Mather and EM-19 holes) indicates that the vertical depths indicated by the surveys are usually deeper than actual vertical depths of the holes. This makes correlation with vertical holes difficult. Indications of coal tops obtained from Dyna-Drill drilling rate changes and from cuttings can also be misleading, especially when drilling nearly horizontally across a formation. Thus it appears that the only method to be certain that the hole is in the target coalbed is to drill well into it or even completely through it.

Horizontal Drilling

It was found that almost all portions of the horizontal holes drilled in rock would cave, making reentry difficult or impossible when the drill pipe was removed. The portions of EM-19 drilled in roof and floor shales were a constant source of problems. In contrast, small diameter (75-100 mm or 3-4 in) horizontal holes drilled in coal from within mines, have consistently been found to stay open for many years, except when drilled in stressed zones near mine openings. The best method developed in the Emerald drilling project to drill horizontal holes was to attempt to follow the regional dip of the coalbed and drill as rapidly as possible. When a hole left the coalbed, a sidetrack, either directly up or down, as required, was performed as soon as it was certain that the hole was really in rock (fig. 19). The sidetrack was started back far enough to provide sufficient distance to avoid immediately drilling out of the coalbed again. The optimum surveying interval for this horizontal drilling program was found to be between 12 and 18 m (40-60 ft). This program was used in drilling the last 600 m (2,000 ft) of H2 and throughout the drilling of H3.

It was found that in horizontal drilling, some type of additives to the drilling fluid are required for removal of cuttings and higher flow rates than can reasonably be run through the Dyna-Drill are required for cleaning the hole. It is recommended that a bypass valve capable of delivering 5.7 to 9.1 m^3/h (25-30 gal/min) to the Dyna-Drill at differential pressures of 3,400 to 4,800 kPa (500-700 lb/in^2g) and bypassing an additional 14 m^3/h (61 gal/min) be used to improve cuttings removal.

Finally, it was learned during the horizontal drilling, that the BQ wireline rod used was not strong enough for this type of drilling. The boxes of the pipe began to open and the pins stretched until even a relatively small pull could separate the pipe at a tool joint. Fortunately, the highest tensile stresses are near the surface and separations usually took place above 180 m (600 ft) MD. It was relatively easy to screw back into the separated joint of pipe, pull it out of the hole, and remove it. However, by the end of the project approximately one-half of the BQ pipe had been rejected as no longer suitable for further drilling. A better pipe for this work would perhaps be a 60-mm (2-3/8 in) o.d. internal and external flush-joint casing or a tubing similar to BQ rod with the same wall thickness and internally flush-joint, but with a slight highly-tapered external upset to strengthen the connections.

Reaming

Both BCQ drill rod (56-mm or 2-3/16-in o.d.) and approximately 1 m (3 ft) long stingers were used to guide the reaming bits along the pilot hole path. It was found that the use of a stinger is the simpler, easier, cheaper, and safer of these two methods of following the pilot hole. However, precautions should be taken to insure that the pilot hole will stay open during reaming. These precautions should include the use of muds to prevent fluid loss to water-sensitive shales which could cause caving of the pilot hole.

In order to reduce the problems of lost circulation, it might also be prudent to plan for the use of an intermediate casing string set below the local water table (since many directional drilling sites are likely to be on hilltops to obtain the required cover for drilling the circular arc). This could mean either splitting up the pilot hole drilling operation by stopping at the first casing point, and then reaming and setting the initial casing before finishing the pilot hole or simply reaming the hole in a larger size to the intermediate casing point.

Bits

It is recommended that diamond bits be used for all of the drilling operations. In particular the 76-mm (3 in) diameter diamond deep cone bit SN-8S54000 (table 3) was found to be very effective for horizontal drilling and allowed rapid sidetracking. In general, the diamond bits were more efficient because of their long life and lower overall cost, due to their high salvage value (tables 3-4). The Strata-Pax bit designs used in this project are not recommended either for reaming or Dyna-Drill use unless significant improvements are made. Testing of tricone bits or hole openers for reaming work would also be worthwhile since even the diamond reaming bits were very inefficient and expensive.

APPENDIX A.--EM-19, DETAILED TIME BREAKDOWN OF DRILLING OPERATIONS

Drilling Operations, Time in Hours

Operations	Pilot hole	Reaming	H1	H2	H3	Total
Normal:						
Drilling or reaming	262.5	475.5	185.5	302.75	182.5	1,408.75
Surveying	86	0	121	246	98.75	552.25
Rig maintenance	3	16.5	4	5.75	1.5	30.75
Circulating hole or lost circulation treatment	47	130.5	50.75	26.5	5	259.75
Plugback	0	0	48	0	0	48
Pipe trip	50.75	85.75	76.25	102.25	15.25	330.25
Startup & shut down	6.25	21	17.25	12.5	6	63
Mix mud & haul water	27.5	128	0	0	0	155.5
Wait on cement	13.75	0	0	0	0	13.75
Stimulation treatment waiting time	0	0	72	0	0	72
Waiting	33	57.25	18.5	41	4.75	154.5
Off days and holidays	240	976	544	336	96	2,192
Total	769.75	1,890.50	1,137.25	1,073.25	409.75	5,280.5
Downtime:						
Fishing	2.25	[1]824	0	16	0	842.25
Mud pumps	59.75	97.25	3.25	6	.75	167
Survey line and pump-down tool	0	0	117.75	20	.5	138.25
Survey instrument	0	0	7.75	6.75	5	19.5
Dyna-Drill	11.5	0	42.75	62.25	3.5	120.0
Pipe and bit failure	6.25	0	0	7.75	8.5	22.5
Rig	115.5	96.75	43.25	0	4	259.5
Total	195.25	1,018	214.75	118.75	22.25	1,569
Grand total	965	2,908.5	1,352	1,192	432	6,849.5

[1]Fishing operations primarily caused by a bit failure.

Percent of Operating Time

	Pilot hole	Reaming	H1	H2	H3	Total
Downtime:						
As a percentage of all time	20.2	35	15.9	10	5.2	22.9
Excluding off time	26.9	52.7	26.6	13.9	6.6	33.7
Drilling:						
As a percentage of all time	27.2	16.4	13.7	25.4	42.3	20.6
Excluding off time	36.2	24.6	23	35.4	54.3	30.3
Excluding off time and downtime	49.6	52	31.3	41	58.2	45.6
Surveying:						
As a percentage of all time	8.9	0	9	20.7	22.9	18.1
Excluding off time	11.9	0	15	28.8	29.4	11.9
Excluding off time and downtime	16.2	0	20.4	33.4	31.5	17.9

APPENDIX B.--PROJECT CHRONOLOGY

Directional Drilling for Degasification of the Pittsburgh Coalbed, Greene County, Pa., DOE Contract No. ET-77-C-01-8891, Originally Bureau of Mines Contract J0377050

Project Initiation and Site Preparation

January 1976	Bureau of Mines began search for new drilling site after termination of Mather directional drilling project.
Mar. 16, 1977	Drilling and directional control requests for proposals (RFP's) released for bid.
Sept. 6, 1977	Cooperative agreement signed with Emerald Mine Corp.
Sept. 27, 1977	Drilling contract signed with Harold F. Scott, Contractor. Original site at Emerald Mine not obtained because of problem with gas rights.
Oct. 1, 1977	Contract transferred to DOE with project management remaining with Bureau of Mines.
Oct. 27, 1977	Modification of contract signed to delay notice to proceed for approximately 90 days due to the Emerald Mines difficulty in finding a new site.
December 1977-March 1978	Coal strike precluded start of drilling operations because of requirement to use UMWA labor.
Jan. 25, 1978	All responses to directional control RFP declared unacceptable.
Feb. 21, 1978	Proposed modification to contract with Harold F. Scott, Contractor, to drill core hole, dewater hole, and subcontract directional control work, submitted to DOE Washington Office staff engineer.
Apr. 7, 1978	Proposed modification to contract with Harold F. Scott, Contractor, to drill seven vertical monitoring holes submitted to DOE Wasington Office staff engineer.
May 1978	Emerald Mines Corp. secured acceptable drilling site.
June 1978	Emerald Mine Corp. began preparation of drilling site.
July 10, 1978	Notice to proceed on original drilling specifications received by Harold F. Scott, Contractor. Actual drilling operations could not proceed pending approval of contract modifications submitted to the DOE, Feb. 21 and Apr. 7, 1978.
Aug. 15, 1978	Contractor began mobilization of equipment to drilling site.
Aug. 22, 1978	Contract with Harold F. Scott, Contractor, modified to include drilling a core hole, dewater hole, and subcontract directional control services. Cost: $385,498.37. (Time required for approval of contract modification, 6 months.)

Core Hole Drilling

Sept. 7, 1978	Contractor began drilling core hole at anticipated location of intercept of the Pittsburgh coalbed by the directional hole.
Sept. 21, 1978	Core hole completed to a depth of 231 m (759 ft).

Dewatering Hole Drilling

Sept. 26, 1978	Contractor began drilling dewater hole with Government-owned drill rig near anticipated intercept of the Pittsburgh coalbed.
Sept. 28, 1978	Contract with Harold F. Scott, Contractor, modified to include the drilling of seven monitoring holes, cost: $443,196.35. (Time required for approval of contract modification, 5-1/2 months.)
Oct. 11, 1978	Emerald Mines Corp. began site preparation for vertical monitoring holes.
Oct. 18, 1978	Drilling of first vertical monitoring hole began. Dewater hole completed to depth of 274 m (900 ft). Casing (178-mm (7-in) o.d.) run and cemented.

Directional Hole Pilot Hole

Nov. 1, 1978	Government-owned rig moved to and set up on directional drilling site.
Nov. 2, 1978	Drilling operations on directional hole begun.
Nov. 21, 1978	Casing jet-slotted adjacent to Pittsburgh coalbed in dewater hole.
Dec. 19, 1978	Pilot hole (76-mm (3-in diameter)) to Pittsburgh coalbed completed to a total measured depth of 503 m (1,649 ft) (305 m true vertical depth).
Dec. 23, 1978- Jan. 2, 1979	Project shut down for Christmas holiday.

Reaming Operation

Jan. 8, 1979	Began overreaming directional hole from 76 to 222 mm (3 to 8-3/4 in).
Jan. 9, 1979	Directional hole reamed to 58 m (191 ft) MD. Severe lost-circulation problems.
Jan. 15, 1979	Began reaming directional hole to 251-mm (9-7/8-in) diameter from surface to 34 m (110 ft) for installation of 244-mm (9-5/8-in) intermediate casing to control lost circulation.
Jan. 23, 1979	Intermediate casing string parted while running to bottom, leaving 9 m (30 ft) stuck in hole.
Jan. 24, 1979	Began recovery operations for stuck casing.
Jan. 26, 1979	Drilling and casing of seven vertical monitoring holes completed.

Jan. 30, 1979	Retrieved 9 m (30 ft) of stuck 244-mm (9-5/8-in) casing. Ran 34 m (112 ft) of new 244-mm (9-5/8-in) casing in directional hole.
Feb. 1, 1979	Pulled worn Strata-Pax bit at 83 m (273 ft) and switched to diamond bit.
Feb. 9, 1979	"Backed off" BCQ wireline rod while pouring lost-circulation-control material in the hole. Began fishing operations to retrieve BCQ rod.
Feb. 13, 1979	Fished 39.6 m (130 ft) of BCQ rod from directional hole. Obtained core of Pittsburgh coalbed from vertical monitoring hole EM-21.
Feb. 20, 1979	Obtained core of Pittsburgh coalbed from vertical monitoring hole EM-22.
Feb. 21, 1979	Changed to flat-faced Strata-Pax bit at depth of 186 m (612 ft). Bit-crown separated from shank at 189 m (620 ft). Began fishing operations.
Feb. 23, 1979	Ran mill to grind up bit-crown. Mill cut 25.4-mm (1-in) pipe at about 36.6 m (120 ft). Began fishing operations for 25.4-mm (1-in) pipe and BCQ rod.
Mar. 13, 1979	Ran downhole TV camera. Removed main string of 25.4-mm (1-in) pipe and all of the BCQ wireline rod.
Mar. 30, 1979	Bit-crown speared and retrieved.
Apr. 4, 1979	Resumed reaming operations with third Strata-Pax bit, using stinger to guide it along the 76-mm (3-in) pilot hole.
Apr. 17, 1979	Strata-Pax bit removed at 257 m (842 ft) due to wear. Second diamond bit run.
Apr. 25, 1979	Obtained core of Pittsburgh coalbed from vertical monitoring hole EM-24.
May 4, 1979	Obtained core of Pittsburgh coalbed from vertical monitoring hole EM-25.
May 9, 1979	Reaming of directional hole completed at 491 m (1,612 ft).
May 10, 1979	Ran 486 m (1,595 ft) of 140-mm (5-1/2-in) casing in directional hole. Obtained core of Pittsburgh coalbed from vertical monitoring hole EM-23.
May 11, 1979	Casing cemented in directional hole.
May 14, 1979	Casing plug drilled out.
May 18, 1979	Drilled 27 m (90 ft) of 76-mm (3-in) horizontal hole in preparation for hydraulic stimulation of EM-20.
May 24, 1979	EM-20 hydraulically stimulated using 79.5m^3 (21,000 gal) foam treatment.

Horizontal Hole Drilling

May 28, 1979	Began drilling horizontal hole H1.
June 6-8, 1979	Shut down while replacing rig clutch. H1 at 716.6 m (2,351 ft) MD.
June 14, 1979	Drilled to 801.9 m (2,631 ft) MD. Pulled back to 674.2 m (2,212 ft) MD to sidetrack.
June 20, 1979	Drilled to 808.3 m (2,652 ft) MD.
June 26, 1979	Proposed modification of contract with Harold F. Scott, Contractor to recover funds expended during unanticipated fishing operations and lost circulation treatments submitted to DOE Washington Office staff engineer.
June 29, 1979	H1 at 910.7 m (2,988 ft) MD.
June 30, 1979- July 8, 1979	Shut down for Independence Day.
July 11, 1979	H1 reaches maximum depth of 1,024.7 m (3,362 ft) MD. After pulling tools to change Dyna-Drill, could not get back into H1.
July 13, 1979	Begin H2 at 491.3 m (1,612 ft) MD.
July 19, 1979	H2 drilled to 701.6 m (2,302 ft) MD. Pulled Dyna-Drill and could not get back to the bottom of H2.
July 20, 1979	Began sidetrack of H2 at 604.1 m (1,982 ft) MD.
July 24, 1979	H2 at 721.2 m (2,366 ft) MD. Dyna-Drill failed and tools pulled. Bit and rotating sub left in the hole.
July 25-26, 1979	Fishing for bit. Bit left in the hole at 642.8 m (2,109 ft) MD in H2-2.
July 30, 1979	Begin sidetrack H2-3 at 591.9 m (1,942 ft) MD.
Aug. 2, 1979	H2 passes 701 m (2,300 ft) MD.
Aug. 9, 1979	Began cleaning the hole with Con-Det and Torque-Trim.
Aug. 14, 1979	H2 drilled to 1,030.8 m (3,382 ft) MD. Pulled tools when Dyna-Drill would not start.
Aug. 15, 1979	Could not get tools past 512.7 m (1,682 ft) MD.
Aug. 16, 1979	Washed drill string back into H2.

Aug. 31, 1979	Completed hole H2 at 1,463.6 m (4,802 ft) MD. A total of 977.5 m (3,207 ft) of horizontal hole.
Sept. 4, 1979	Begin sidetracking H3 at 497.4 m (1,632 ft) MD.
Sept. 12, 1979	H3 at 927.2 m (3,042 ft) MD.
Sept. 18, 1979	Contract with Harold F. Scott, Contractor, modified to recover funds expended during unanticipated fishing operations and lost-circulation treatments. Modification value: $244,764.26. (Time required for approval of contract modification, 2-3/4 months.)
Sept. 21, 1979	H3 at total depth of 1,398.4 m (4,588 ft) MD.
Sept. 26, 1979	H4 started at 488.3 m (1,602 ft) MD.
Oct. 1, 1979	H4 terminated at 750.4 m (2,462 ft) MD. H5 started at 488.3 m (1,602 ft) MD.
Oct. 5, 1979	H5 terminated at 701.6 m (2,302 ft) MD.

Underreaming

Oct. 8-9, 1979	EM-19 opened from 76 to 216 mm (3 to 8-1/2 in) between 486.2 and 531 m (1,595-1,742 ft) MD. Hole entered coal at 522 m (1,712 ft) MD.

Well Completion Work

Oct. 10, 1979	Proposed modification to contract with Harold F. Scott, Contractor, for a no-cost time extension to May 26, 1980, submitted to DOE Methane from Coalbeds project manager, Morgantown, W. Va.
Oct. 15-20, 1979	Cleaned out and bailed water from EM-20.
Oct. 22-26, 1979	Bailed and swabbed EM-20.
Oct. 26, 1979	Contract with Harold F. Scott, Contractor, modified for a no-cost time extension to May 26, 1980. (Time required for approval of contract modification, 16 days.)
Nov. 5, 1979	Ran tubing and rods in EM-20.
Nov. 6-7, 1979	Pumped EM-20 with spudding rig. Installed EM-19 wellhead.
Nov. 9, 1979	Set pumping unit on EM-20.
Nov. 15, 1979	Mine hooked up power lines to EM-20. Begin pumping water at 20.4 m^3/d (128 bbl/d).

Well Testing and Production

Dec. 4-7, 1979	Attempted to circulate water in EM-19 to clean up well and increase water production at EM-20.

Dec. 17-19, 1979	Pumped water into EM-20 at up to 8,860 kPa (1,285 lb/in^{2}g) and 0.15 to 0.3 m^3/min (1-2 bbl/min) in attempt to fracture the coal and move cuttings to EM-19. Circulate water at EM-19 to remove cuttings.
Dec. 20-21, 1979	Using compressed-air lift to dewater EM-19. EM-20's sucker rod pump also pumping.
Dec. 27, 1979	Working on EM-19 wellhead equipment.
Dec. 28, 1979	Set up flare stack for EM-19.
Jan. 2, 1980	Completed EM-19 flare stack. Ran BQ rod to 335 m (1,100 ft) in EM-19 to air lift water from the hole. Began air lift at 1245 hours. Shut down at 1530 hours.
Jan. 3, 1980	Blowing water from EM-19 between 0800 and 1600 hours. Ran BQ rod to 515 m (1,690 ft) MD (in the open hole). Putting up the flare stack on EM-20.
Jan. 4, 1980	Blowing water from EM-19 between 0800 and 1600 hours. Completed installing flare stack on EM-20.
Jan. 7-8, 1980	Blowing water from EM-19 between 0800 and 1600 hours. Pulled pipe back to 484.6 m (1,590 ft).
Jan. 9, 1980	Blowing water from EM-19 (0800 to 1600 hours). Installed float water-level sensor in EM-27.
Jan 10, 1980	Blowing water from EM-19 (0800 to 1600 hours). Total production, approximately 40 m^3 (250 bbl). Float devices hooked up on EM-21, 25, and 26.
Jan. 11, 1980	Blowing water from EM-19 (0800-1600 hours). Floats hooked up on EM-22, 23, and 24.
Jan. 14, 1980	Blowing water from EM-19 (0800 to 1600 hours). Total production 58 m^3 (365 bbl). Pulled pump and rods from EM-20. Pumped approximately 36 m^3 (225 bbl) of water into EM-20 at 6,500 to 6,890 kPa (950-1,000 lb/in^{2}g) surface pressure between 1145 and 1338 hours.
Jan. 15, 1980	Blowing water from EM-19 (0800 to 1600 hours). Total production 46.6 m^3 (293 bbl). Pumped approximately 71.5 m^3 (450 bbl) of water into EM-20 at 6,200 to 7,240 kPa (900-1,050 lb/in^{2}g) surface pressure, between 0935 and 1500 hours.
Jan. 16, 1980	Blowing water from EM-19 (0800 to 1600 hours). Ran pipe to 515.1 m (1,690 ft) MD. Pumped approximately 79 m^3 (500 bbl) of water into EM-20 between 0900 and 1500 hours.
Jan. 17, 1980	Blowing water from EM-19 (0800 to 1600 hours). Total production 62 m^3 (392 bbl). Pulled BQ rod back to 457.2 m (1,500 ft) MD. Ran pump and rods back into EM-20, and put it back on water production.

Jan. 18, 1980	Blowing water from EM-19 (0800 to 1600 hours). Total production 51 m^3 (319 bbl). EM-20 gas production 59 m^3/d (2,080 ft^3/d), water 16.4 m^3/d (103 bbl/d). Well not yet pumped down.
Jan. 21, 1980	Blowing water from EM-19 (0800 to 1600 hours). Total 33 m^3 (207 bbl). EM-20 gas flow 218 m^3/d (7,720 ft^3/d), water 7.3 m^3/d (46 bbl/d).
Jan. 22, 1980	Start blowing EM-19 around the clock at 0001. Total for 24 hours, 78 m^3 (491 bbl). EM-20 gas production 153 m^3/d (5,400 ft^3/d), water 2.1 m^3/d (13 bbl/d).
Jan. 23, 1980	Blowing water from EM-19 (24 hours). Total production 51 m^3 (321 bbl).
Jan. 24, 1980	Blowing water from EM-19 (24 hours). Total production, 39 m^3 (247 bbl). EM-20 gas flow 251 m^3/d (8,870 ft^3/d), water 1 m^3/d (6 bbl/d).
Jan. 25, 1980	Blowing EM-19 until 1100 hours. Total water production, 19 m^3 (119 bbl). Pulled BQ rod out of the hole at 1110 hours. EM-20 gas flow 323 m^3/d (11,400 ft^3/d), water 1 m^3/d (6 bbl/d).
Jan. 28, 1980	EM-20 production, gas 137 m^3/d (4,850 ft^3/d), water 5 m^3/d (31.6 bbl/d).
Feb. 4, 1980	Ran BQ rod in EM-19.
Feb. 5, 1980	Blowing water from EM-19, 1220 to 1600 hours. EM-20 gas flow 66 m^3/d (2,320 ft^3/d), water 4.7 m^3/d (29.4 bbl/d).
Feb. 6, 1980	Blowing EM-19, 0845 to 2400 hours. Total water production 53 m^3 (336 bbl). EM-20 gas flow 131 m^3/d (4,650 ft^3/d), water 3.1 m^3/d (19.5 bbl/d).
Feb. 7, 1980	Blowing EM-19 (24 hours). Total water production 52 m^3 (330 bbl). EM-20 pump, rods, and tubing pulled at 1120 hours.
Feb. 8, 1980	Blowing EM-19 until 1530 hours. Pumped water into EM-20, 1034 to 1142 hours and 1259 to 1415 hours at 1.6 to 2.4 m^3/h (10-15 bbl/min). Maximum surface pressure 9,860 kPa (1,430 lb/in^2g), average pressure 8,600 kPa (1,250 lb/in^2g). Total volume pumped 217 m^3 (1,363 bbl).
Feb. 11, 1980	Put pump back in EM-20. Pump on continuously through May 31, 1980.
Feb. 12, 1980	EM-20 gas flow 64 m^3/d (2,270 ft^3/d), water 20.4 m^3/d (128.5 bbl/d).
Feb. 13, 1980	Emerald Mine begins pumping water from No. 2 return shaft near EM-25. Depth to Pittsburgh coal 189 m (620 ft).
Feb. 15, 1980	Air shaft water level down 11 m (35 feet) from surface.

Feb. 19, 1980	EM-20 gas flow 104 m^3/d (3,670 ft^3/d), water 14.9 m^3/d (93.5 bbl/d). Shaft water level 61 m (200 ft).
Feb. 21, 1980	Increase stroke rate on EM-20 pump from 14 to 15-1/2 strokes per minute. Water production not affected. EM-20 gas flow 141 m^3/d (4,980 ft^3/d), water 14.9 m^3/d (93.5 bbl/d).
Feb. 24-29, 1980	EM-25 water level begins to drop due to shaft dewatering.
Feb. 25, 1980	Shaft water level 105 m (345 ft) at 2330 hours. EM-20 gas flow 114 m^3/d (4,030 ft^3/d), water 9.1 m^3/d (57 bbl/d).
Feb. 26, 1980	Reduce EM-20 stroke rate back to 14 strokes per minute. Shaft water level 114 m (374 ft) below surface.
Feb. 27, 1980	Shaft water level 121 m (398 ft) at 1530 hours. EM-20 gas flow 37 m^3/d (1,310 ft^3/d), water 9.3 m^3/d (58.8 bbl/d).
Feb. 28, 1980	Shaft water level 145 m (475 ft) at 2000 hours. EM-20 gas flow 78 m^3/d (2,760 ft^3/d), water 8.8 m^3/d (55.6 bbl/d).
Feb. 29, 1980	Shaft water level 142 m (465 ft). EM-20 gas flow 110 m^3/d (3,890 ft^3/d), water 7.9 m^3/d (50 bbl/d).
Mar. 3, 1980	Bailing muck from air shaft, water level 152 m (500 ft).
Mar. 4, 1980	Shaft water level 168 m (550 ft). EM-20 gas flow 118 m^3/d (4,160 ft^3/d), water 7.8 m^3/d (49 bbl/d).
Mar. 13, 1980	Ordered submersible pump for EM-19. EM-20 gas flow 132 m^3/d (4,650 ft^3/d), water 6.4 m^3/d (40.3 bbl/d).
Mar. 14, 1980	Air shaft dewatered to the Pittsburgh coalbed, at 189 m (620 ft). Water level in EM-19, 130 m (430 ft) above the Pittsburgh coalbed, or about 1,280 kPa (186 lb/in^2g).
Mar. 15, 1980	Air shaft cut into by mining from 1 West return section.
Mar. 17, 1980	Swabbing rig moved to EM-24. Begin swabbing at 1055 hours with initial swabbing depth 51.5 m (168.9 ft). Removed 2.4 m^3 (640 gal) from hole by 1600 hours, 1.2 m^3 (327 gal) of which was in the casing initially. EM-20 gas flow 141 m^3/d (4,980 ft^3/d), water 6.1 m^3/d (38.5 bbl/d).
Mar. 18, 1980	Initial water level in EM-24, 59.4 m (195 ft). Swabbed 1.9 m^3 (500 gal). EM-20 gas flow 133 m^3/d (4, 710 ft^3/d), water 6.2 m^3/d (38.8 bbl/d).
Mar. 19, 1980	Initial water level in EM-24, 152 m (500 ft). Swabbed 0.5 m^3 (120 gal) and shut down after 1200 hours so that the pressure reductions caused by the air shaft could be determined.
Mar. 20, 1980	Filled EM-24 and put the water level sensor back on. EM-20 gas flow 141 m^3/d (4,980 ft^3/d), water 6.3 m^3/d (39.6 bbl/d). EM-19 gas flow zero.

Mar. 21, 1980	EM-20 gas flow 147 m^3/d (5,200 ft^3/d), water 5.6 m^3/d (35.5 bbl/d). EM-19 gas flow 25 m^3/d (872 ft^3/d).
Mar. 24, 1980	EM-20 gas flow 309 m^3/d (10,900 ft^3/d), water 6.5 m^3/d (41 bbl/d). EM-19 gas flow 79 m^3/d (2,800 ft^3/d).
Mar. 26, 1980	EM-20 gas flow 277 m^3/d (9,800 ft^3/d), water 6.3 m^3/d (39.7 bbl/d). EM-19 gas flow 66 m^3/d (2,320 ft^3).
Mar. 27, 1980	EM-20 gas flow 272 m^3/d (9,600 ft^3/d), water 6.0 m^3/d (38 bbl/d). EM-19 gas flow 63 m^3/d (2,210 ft^3/d).
Apr. 1, 1980	EM-20 gas flow 283 m^3/d (10,000 ft^3/d), water 5.9 m^3/d (37.4 bbl/d). EM-19 gas flow 61 m^3/d (2,160 ft^3/d). Ditch dug to run power line to EM-19 wellhead for the submersible pump.
Apr. 8, 1980	EM-20 gas flow 294 m^3/d (10,370 ft^3/d), water 5.3 m^3/d (33.2 bbl/d). EM-19 gas flow 73 m^3/d (2,570 ft^3/d).
Apr. 15, 1980	EM-20 gas flow 304 m^3/d (10,730 ft^3/d), water 5.0 m^3/d (31.6 bbl/d). EM-19 gas flow 76 m^3/d (2,670 ft^3/d).
Apr. 23, 1980	Submersible pump, cable, and control box delivered to EM-19 drilling site. EM-20 gas flow 314 m^3/d (11,080 ft^3/d), water 4.9 m^3/d (30.7 bbl/d). EM-19 gas flow 79 m^3/d (2,800 ft^3/d).
Apr. 28, 1980	Submersible pump run in directional hole.
Apr. 29, 1980	Submersible pump pulled from hole. Wires cut by centralizer. EM-20 gas flow 342 m^3/d (12,080 ft^3/d), water 4.5 m^3/d (28.2 bbl/d). EM-19 gas flow not measured.
May 5, 1980	Submersible pump run again. Splice leaked and shorted out pump after 1 hour of operation.
May 7, 1980	Respliced submersible pump cable. EM-20 gas flow 384 m^3/d (13,580 ft^3/d), water 4.2 m^3/d (26.7 bbl/d). EM-19 gas flow 83 m^3/d (2,940 ft^3/d).
May 8, 1980	Pump run in EM-19 and check valve broke at 36 m (120 ft). Pump pulled from the hole using the cable.
May 9, 1980	Prepared to run pump in EM-19 but found that the motor seals had failed when check valve broke and put tension on the cable.
May 12, 1980	Motor sent to REDA Columbus repair facility to be resealed. A new motor also purchased. EM-20 gas flow 388 m^3/d (13,720 ft^3/d), water flow 4.3 m^3/d (27 bbl/d). EM-19 gas flow 72 m^3/d (2,550 ft^3/d).
May 14, 1980	Submersible pump run in EM-19. Initial water flow 2.6 m^3/h (11.5 gal/min). EM-20 gas flow 392 m^3/d (13,860 ft^3/d), water flow 3.9 m^3/d (24.5 bbl/d). EM-19 gas flow 69 m^3/d (2,430 ft^3/d).

May 15-16, 1980 — Pump run during daylight hours only for testing purposes. During this period it was found that gas entering the pump was causing it to shut off without pumping the hole dry. At the end of the 16th the pump was put on full time operation.

May 19, 1980 — EM-20 gas flow 469 m^3/d (16,580 ft^3/d), water 3.4 m^3/d (21.4 bbl/d). EM-19 gas flow rates not measured.

May 20, 1980 — EM-20 gas flow 452 m^3/d (15,980 ft^3/d), water 3.5 m^3/d (21.7 bbl/d). EM-19 gas flow 141 m^3/d (4,980 ft^3/d), water flow intermittent but less than 1.6 m^3/d (10 bbl/d).

May 23, 1980 — Last working day of contract. All equipment keys, etc., turned over to Government.

May 30, 1980 — EM-20 gas flow 452 m^3/d (15,980 ft^3/d), water 3.6 m^3/d (22.8 bbl/d). EM-19 gas flow 157 m^3/d (5,540 ft^3/d), water flow 1.0 m^3/d (6 bbl/d).

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