RI 9102

Bureau of Mines Report of Investigations/1987

Accurate Directional Borehole Drilling: A Case Study at Navajo Dam, New Mexico

By S. J. Kravits, A. Sainato, and G. L. Finfinger

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 9102

Accurate Directional Borehole Drilling: A Case Study at Navajo Dam, New Mexico

By S. J. Kravits, A. Sainato, and G. L. Finfinger

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
David S. Brown, Acting Director

Library of Congress Cataloging in Publication Data:

Kravits, S. J. (Stephen J.)
Accurate directional borehole drilling.

(Report of investigations ; 9102)

Bibliography: p. 18.

Supt. of Docs. no.: I 28.23: 9102.

1. Directional drilling–New Mexico–Navajo Dam. I. Sainato, Albert. II. Finfinger, Gerald L. III Title. IV. Series: Report of investigations (United States. Bureau of Mines) ; 9102.

TN23.U43 [TN279] 622 s [622'.23] 87-600008

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

EMU	electromagnetic unit	lbf	pound force
ft	foot	min	minute
ft•lbf	foot pound (force)	nT	nanotesla
gal/min	gallon per minute	psi	pound per square inch
hp	horsepower	psig	pound per square inch, gauge
in	inch	r/min	revolution per minute
in/min	inch per minute	V ac	volt, alternating current

ACCURATE DIRECTIONAL BOREHOLE DRILLING: A CASE STUDY AT NAVAJO DAM, NEW MEXICO

By S. J. Kravits,[1] A. Sainato,[2] and G. L. Finfinger[3]

ABSTRACT

This report describes a project conducted by the Bureau of Mines in which the accurate directional drilling of a borehole was demonstrated with the objective of intercepting a designated target. The project was conducted at Navajo Dam in northern New Mexico at the request of the Bureau of Reclamation. Borehole survey and drill logs are provided in an appendix.

The trajectory of the demonstration borehole was designed to intercept a 5-ft-radius target at the final or "punchout" distance of 885 ft. The elevation of the borehole at this distance was within the target; the borehole punchout coordinates were 8.81 ft southwest of the target. As a result of the demonstrated accuracy, the Bureau of Reclamation has contracted the accurate drilling of boreholes as long as 600 ft from the inside of a short tunnel, to control water seepage in the right abutment. This resulted in a substantial cost savings compared to the original plan of constructing a longer tunnel and drilling 150-ft boreholes.

---

[1] Mining engineer.
[2] Mining engineering technician.
[3] Supervisory geologist.
Pittsburgh Research Center, Bureau of Mines, Pittsburgh, PA.

INTRODUCTION

The Bureau of Reclamation, U.S. Department of the Interior, requested the Bureau of Mines, through Interagency Agreement No. 1409-0070-1212, to demonstrate the accuracy of directional drilling a near-horizontal borehole to intercept a designated target. The Bureau of Reclamation's objective was to determine the feasibility of using accurately drilled boreholes to control water seepage through open joints in bedrock foundations of embankment dams.

The Bureau of Mines has researched and demonstrated accurate directional drilling as part of its methane control program (1-3).[4] In 1979, a directional surface borehole was drilled using an in-hole motor[5] to a measured depth of 1,595 ft, maintaining an arc of 6° per 100 ft and coming within 3 ft of intercepting the Pittsburgh Coalbed 1,012 ft below the surface. Five horizontal methane drainage boreholes were then drilled from the surface borehole, totaling 9,544 ft.

The Bureau has also demonstrated drilling accuracy in drilling long horizontal methane drainage boreholes in underground coal mines. Methane drainage boreholes have been drilled to depths greater than 2,000 ft, maintaining vertical borehole trajectory within the coalbed (approximately 6 ft) while controlling horizontal trajectory as desired to prevent interception by future mining (2-3).

ACKNOWLEDGMENTS

The cooperation of the Bureau of Reclamation was critical in the successful completion of this project. The authors wish to thank Hunter C. Harrel, geologist, Engineering and Research Center, Denver, CO; William C. Ehler, geologist, Durango (CO) Projects Office; Leonard Trujillo, Navajo Dam superintendent; and Navajo Dam maintenance staff for their continued support and assistance during this project. The authors also thank Ed J. Blythe, Jr., well planning engineer, NL Sperry-Sun, Rosenburg, TX for technical assistance provided in improving surveying accuracy.

TEST SITE

Navajo Dam is a zoned embankment structure in northern New Mexico, 39 miles east of Farmington, NM, and about 35 miles southeast of Durango, CO (fig. 1). It is one of the key structures of the Colorado River Storage Project, regulating the flows of the San Juan River and providing storage for Navajo Indian Irrigation Project. It also provides a facility for recreation and fish and wildlife conservation. Navajo Dam, constructed from 1958 to 1963, is approximately 400 ft in structural height, 3,600 ft in crest length, 30 ft in top width, and 2,500 ft in maximum base width (4). The right abutment of the dam was chosen for the loaction of the demonstration borehole, with designed punchout occurring near the top of the spillway (figs. 2-3).

---

[4] Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

[5] The term in-hole is synonymous with downhole. The authors feel in-hole is more descriptively accurate when borehole trajectory is near horizontal.

DRILLING EQUIPMENT

A Diamant Boart[6] DBH 700 hydraulic core drill and a 2-7/8-in-OD high-torque, nonmagnetic in-hole motor manufactured by Slimdril, Inc., were used to drill the borehole. The in-hole motor was equipped with a bent housing and two 3-1/2-in-OD polycrystalline diamond cutter bits (used separately), one manufactured by Longyear and one by Slimdril, Inc.

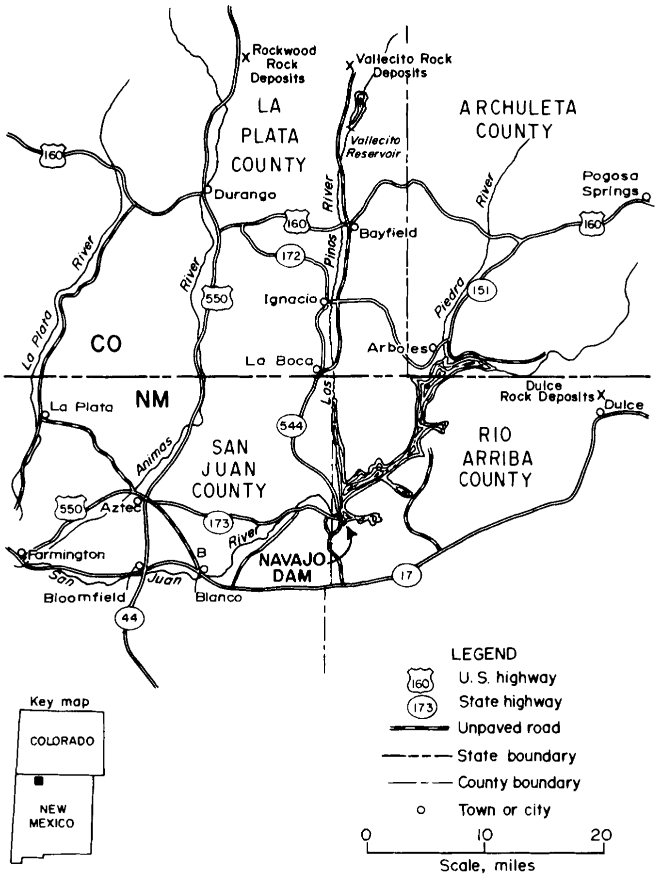


FIGURE 1.—Navajo Dam location map. Adapted from Bureau of Reclamation map.

HYDRAULIC DRILL

The main components of the Diamant Boart DBH 700 unit are the drill itself, control panel, and power unit (fig. 4). To drill the demonstration borehole, the drill was positioned horizontally. The power unit is equipped with two hydraulic radial piston pumps, one for thrust and one for rotation, both powered by a single 40-hp, 440-V ac electric motor.

IN-HOLE MOTOR

The 2-7/8-in-OD high-torque in-hole motor is a positive-displacement hydraulic motor that rotates the drill bit without rotating the drill string. The in-hole motor converts the hydraulic horsepower generated by the flow of the drilling fluid (water) under pressure into torque and into the rotational speed or mechanical power that drives the drill bit (5). The components of the high-torque motor are identified in figure 5.

When drilling fluid is pumped through the drill string and the in-hole motor at rates of 30 to 70 gal/min at differential pressures of 250 to 625 psig, the helical stainless steel rotor rotates inside the rubber molded stator. The range of Slimdril operating parameters is shown in figure 6; the actual parameters applied are listed in table A-1 (appendix). Rotation of the drive shaft, positioned within the bearing package, is transmitted by the flex-coupling, converting the eccentric rotary motion of the helical rotor to concentric motion. The drive sub is connected to the drive shaft and is the only rotating external component of the in-hole motor. The drill bit is fastened to the drive sub. Two 3-1/2-in-OD polycrystalline diamond cutter bits, one each from Longyear and Slimdril, Inc., were equally used to drill

---

[6] Reference to specific equipment does not imply endorsement by the Bureau of Mines.

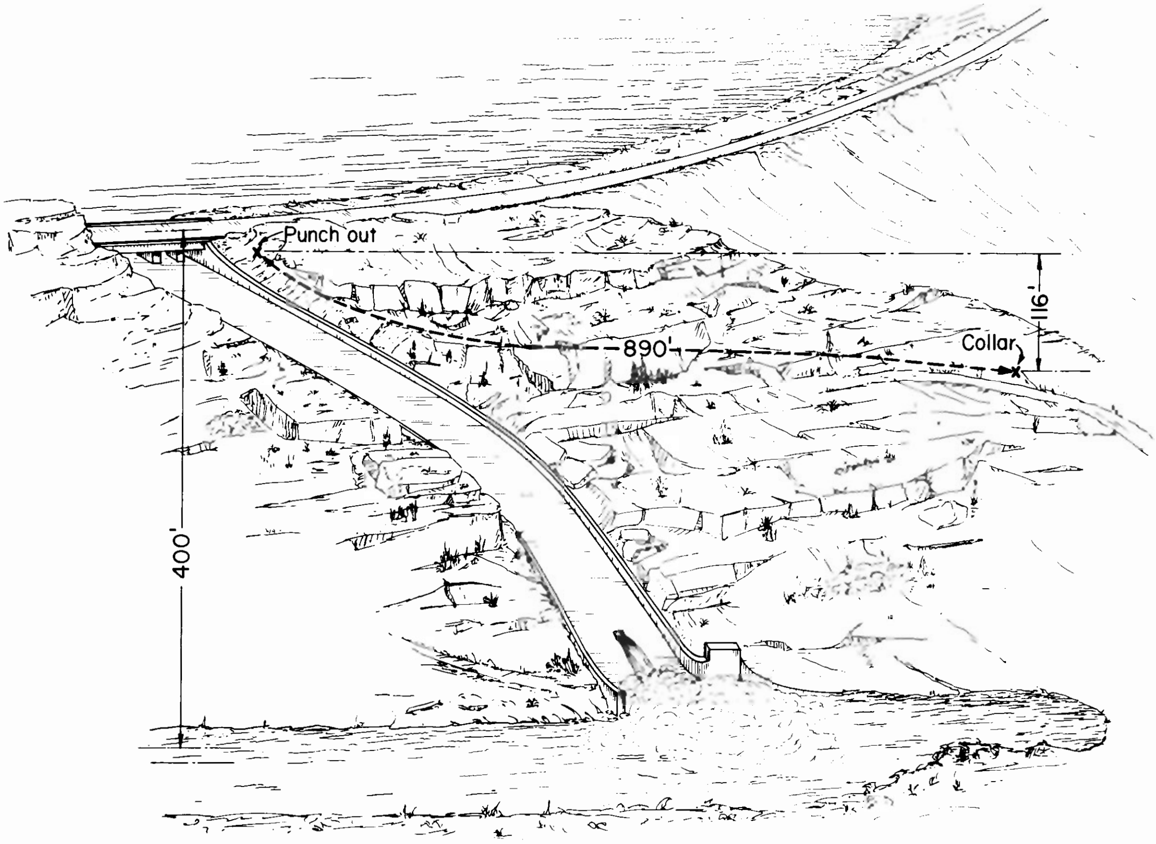


FIGURE 2.—Navajo Dam right abutment.

FIGURE 3.—Navajo Dam demonstration borehole drill site.

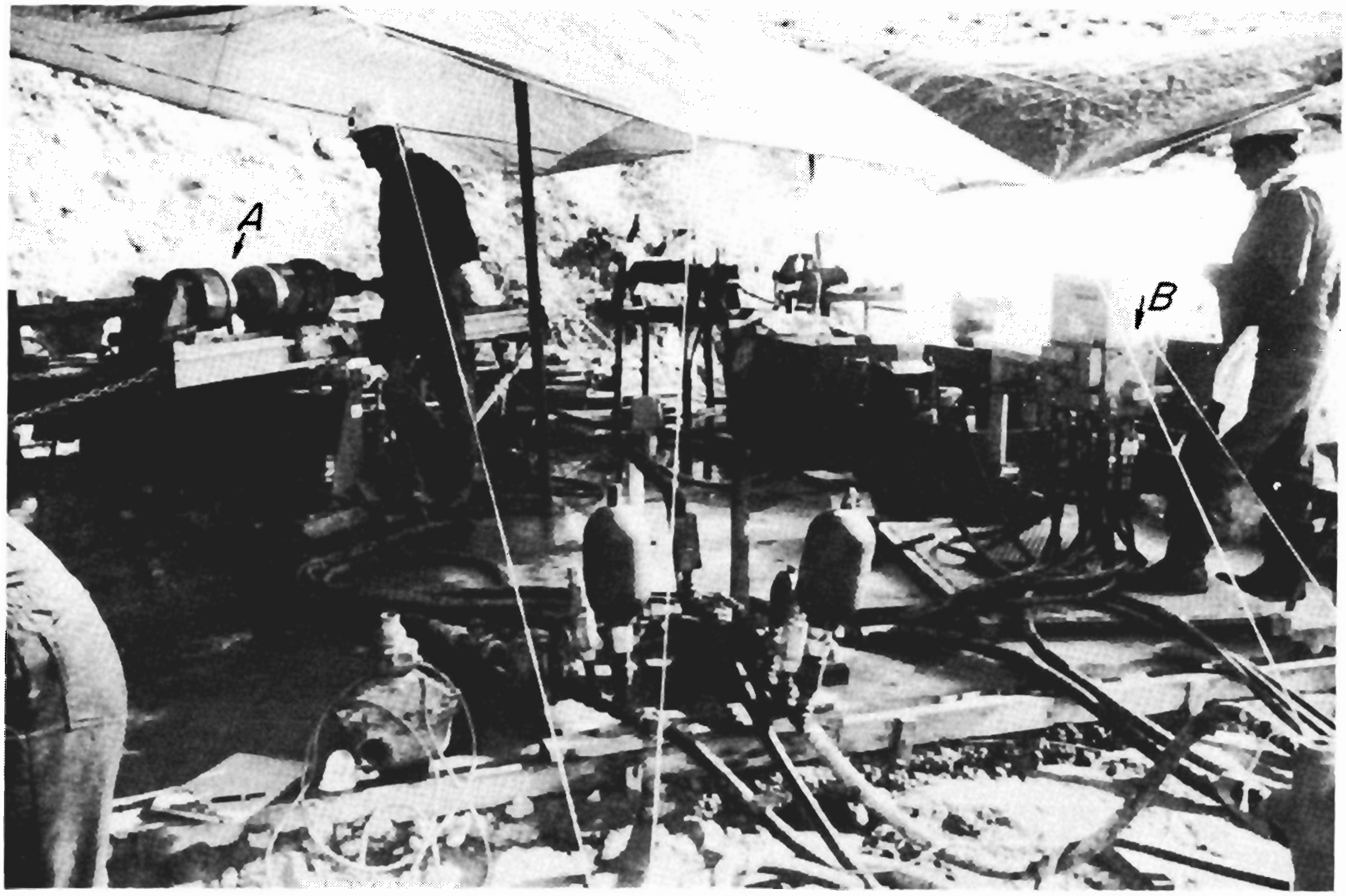
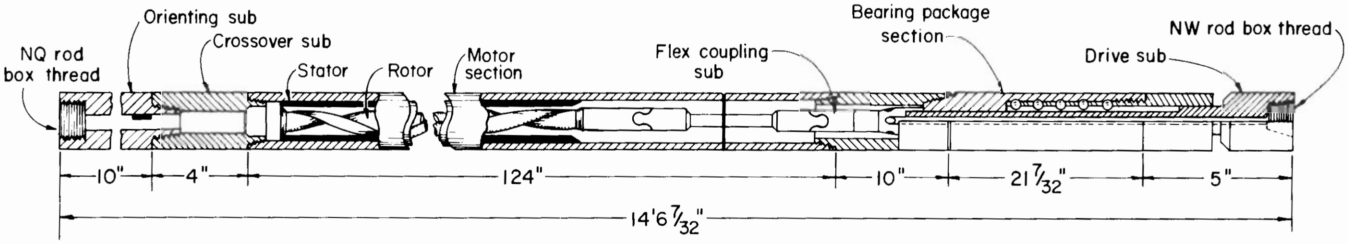


FIGURE 4.—*A*, Hydraulic drill; *B*, control panel. Power unit not shown.



Not to scale

FIGURE 5.—In-hole motor schematic. Stator, rotor and exterior housing are nonmagnetic. Bearing package and drive sub are magnetic.

the demonstration borehole (fig. 7). Polycrystalline diamond cutter bits are recommended for use with in-hole motors because they are designed to operate at high rotating speeds for extended periods. The demonstration borehole's horizontal and vertical borehole trajectories were controlled during in-hole motor drilling by using control devices.

BOREHOLE TRAJECTORY CONTROL DEVICES

Various types of devices can be used with in-hole motors to control borehole trajectory. These include bent housings, bent subs, eccentric subs, and deflection shoes. An in-hole motor equipped with a 2° bent housing is shown in figure 8.

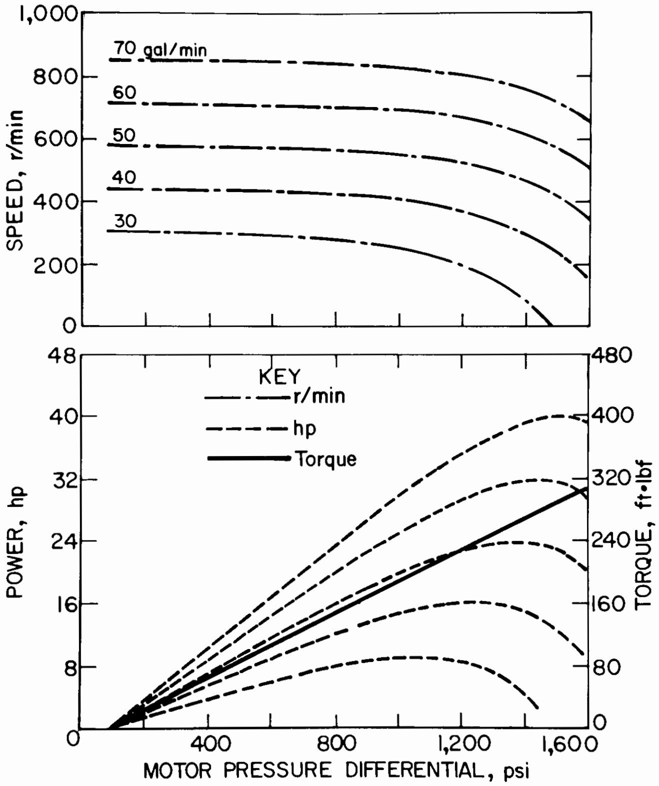


FIGURE 6.—In-hole motor operating parameters. Water supplied to in-hole motor under pressure by two triple-piston pumps.

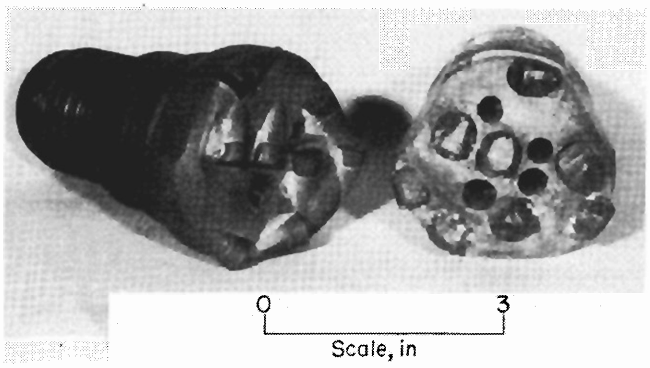


FIGURE 7.—Polycrystalline diamond cutter bits.

While drilling, there is continuous contact between the convex side of the bent housing and the wall of the borehole; this is commonly called side force. The resultant reaction of the side force exerted on the wall of the borehole is a force exerted on the bit in the opposite direction or 180° away (fig. 9). The direction of the force exerted on the bit is called tool face direction and is the direction borehole trajectory will follow. Various tool face settings and their effects on borehole vertical and horizontal trajectories are shown in figure 10.

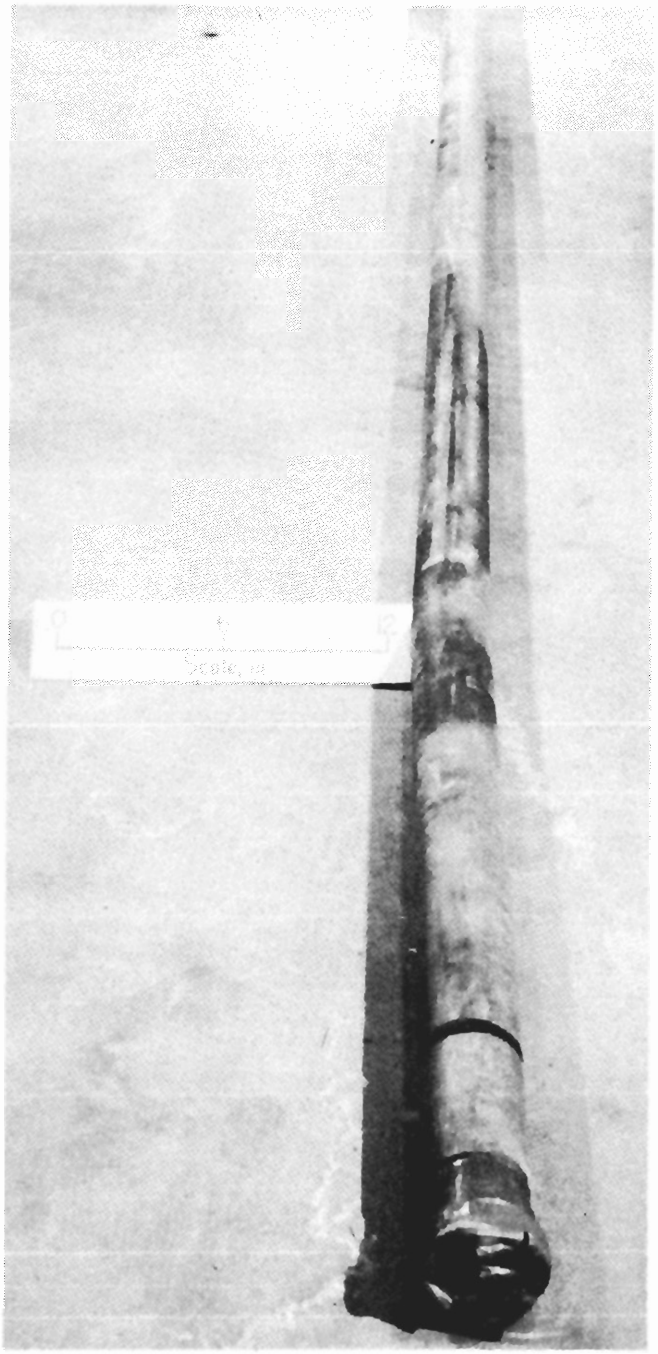


FIGURE 8.—In-hole motor equipped with a 2° bent housing.

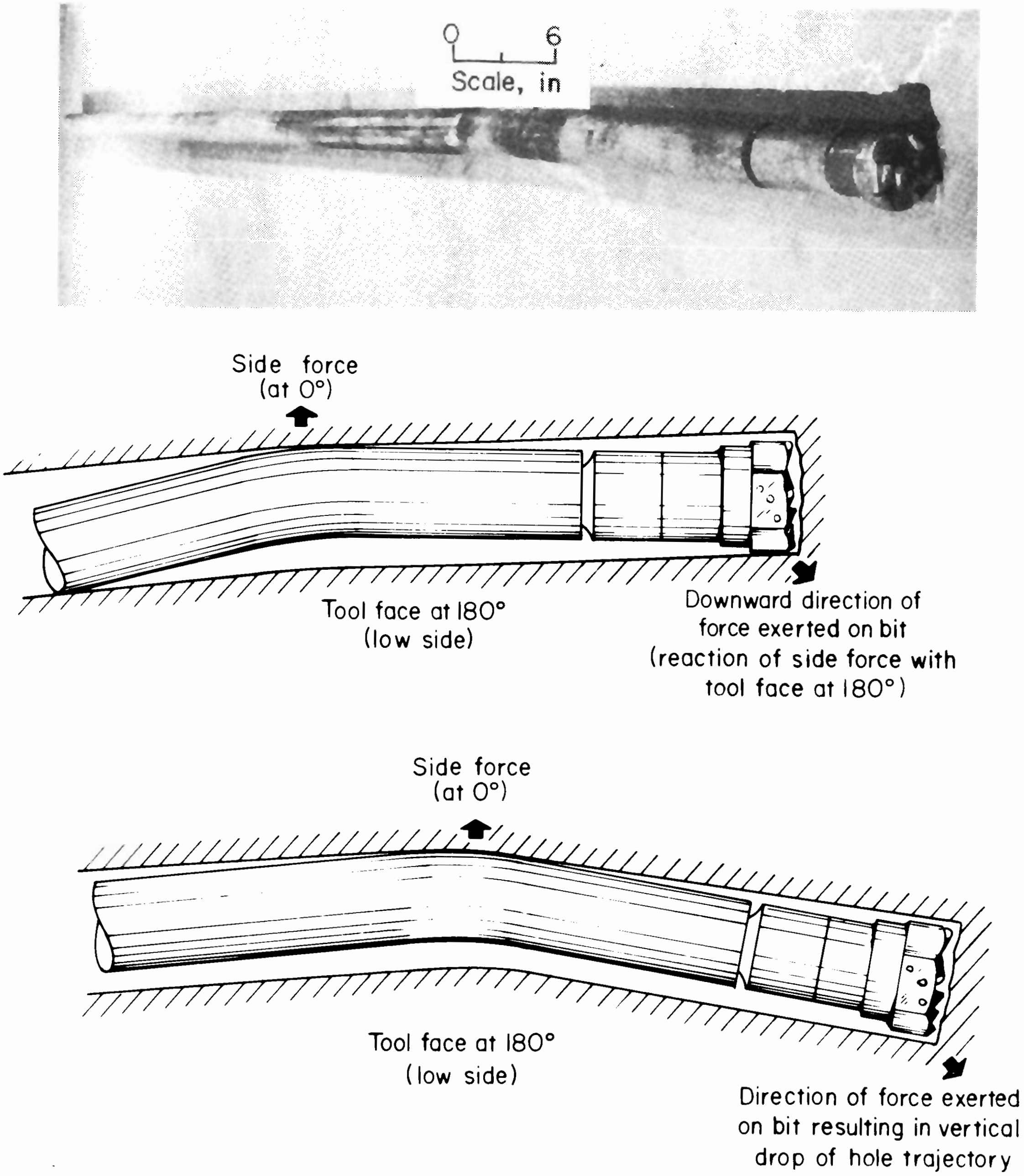


FIGURE 9.—Side force diagram. Above in-hole motor equipped with bent housing; below, side force schematic.

Deflection rates pertaining to known tool face settings are rates at which borehole inclination and azimuth (bearing) change or deflect during drilling. The rate of change in borehole inclination is the vertical deflection rate; the horizontal deflection rate is the rate of change in azimuth. Established deflection rates would be used to periodically project or estimate bit position 16 ft ahead of the current survey depth and to decide what tool face setting should be applied to the next drilling interval in order to maintain desired borehole trajectory. Vertical and horizontal deflection rates are determined by

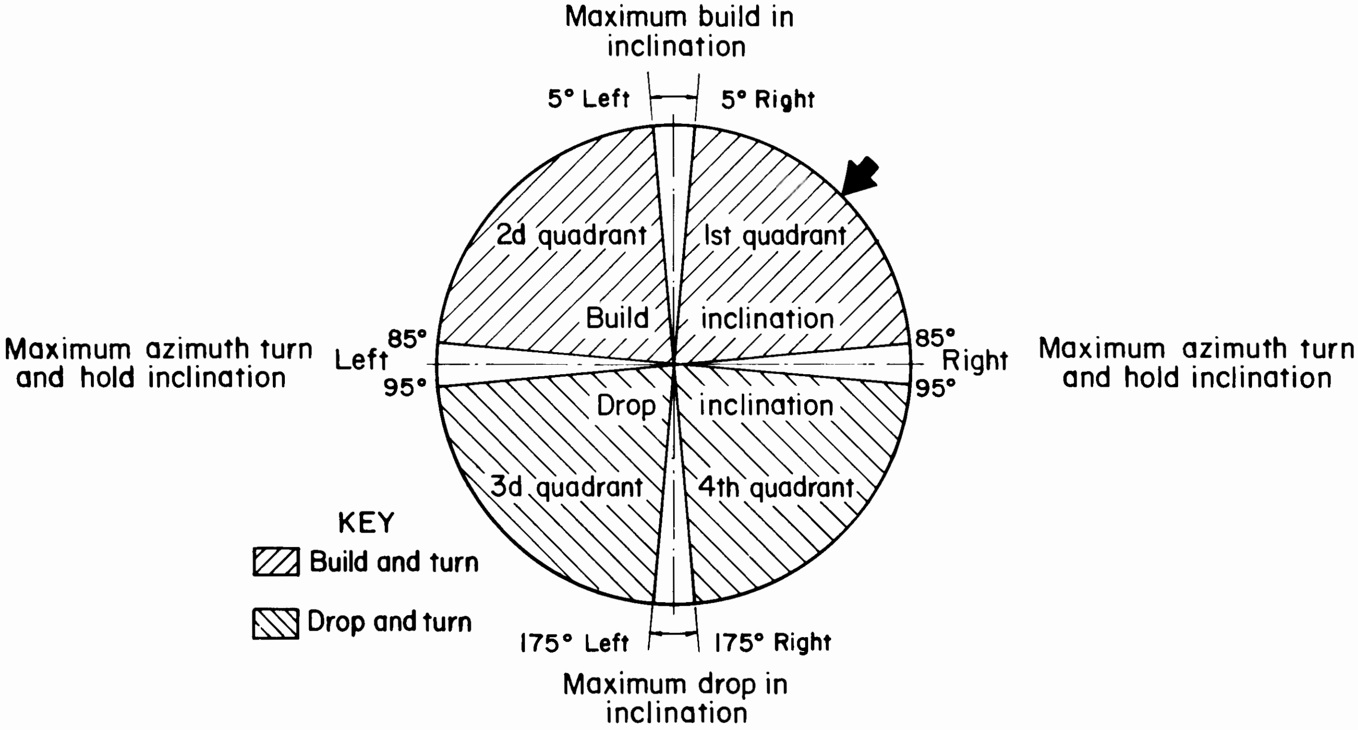


FIGURE 10.—Various tool face settings and their effects on borehole trajectory. Black arrow depicts tool face setting of 45° right, which would result in borehole trajectory building inclination and azimuth turning right (east).

observing the change in inclination and azimuth from the previous to the current borehole survey depth. For example, referring to the third page of table A-2, the vertical and horizontal deflection rates observed from survey depths 449 to 459 ft were 0.09°/ft (0.9° during 10-ft interval) and 0.19°/ft (east is positive), respectively. A tool face setting of 60° to 80° right was applied using a 2° bent housing while drilling from 445 to 475 ft. When the survey was conducted at 459 ft, the bit depth was 475 ft. To project the inclination at the bit depth of 475 ft, the established vertical deflection rate of 0.09°/ft was multiplied by 16 ft and added to the surveyed inclination at 459 ft. This resulted in a projected inclination of 101.8°. The azimuth at the bit depth was projected to be 343.0° by multiplying the horizontal deflection rate of 0.19°/ft by 16 ft and adding the azimuth surveyed at 459 ft of 340.0°. The projected inclination and azimuth at 475 ft were close to the actual results surveyed later at 479 ft (table A-2). Angle averaging, which is a surveying calculation method, was used to calculate projected coordinates and elevation at the bit (_2_, _6_). Established deflection rates pertaining to tool face settings and bent housing used are provided later in the text.

Tool face directions are changed by turning the drill string clockwise with pipe wrenches to a position 0° to 180° left or right from the centerline along the top of the boring. Borehole inclination, azimuth, and tool face direction were continuously monitored and adjusted to achieve directional control or to maintain the desired horizontal and vertical borehole trajectories.

SURVEYING EQUIPMENT AND PROCEDURES

SINGLE-SHOT SURVEY INSTRUMENT

An NL Sperry-Sun type B 120° magnetic directional single-shot survey instrument was used during drilling to monitor borehole inclination, bearing, and tool face direction (fig. 11). The essential elements of the survey instrument are the compass, inclination unit, batteries and film loading mechanism, lens and lamp holder, and mechanical timer that controls the electrical circuits and illuminates the compass-inclination unit at a preset time to record the pertinent data on a film disk (7).

To conduct a survey, the mechanical timer of the survey instrument is set and the instrument is loaded with a film disk. The loaded survey instrument is placed in its protective casing and inserted in the hollow drill rod. It is pumped with water to the back end of the in-hole motor, where it aligns with the orienting sub. The film disk is exposed at a preset time, after which the instrument is retrieved by a wireline attached to the protective casing. The retrieved instrument is removed from its protective casing, and the film disk is removed, developed, and read (fig. 12).

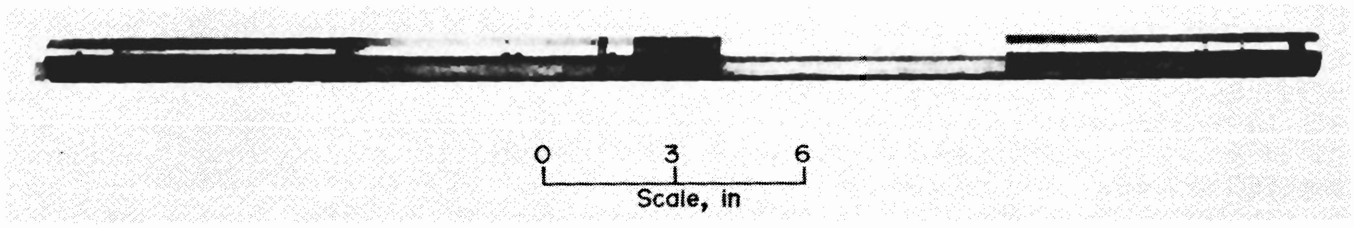


FIGURE 11.—Single-shot directional survey instrument.

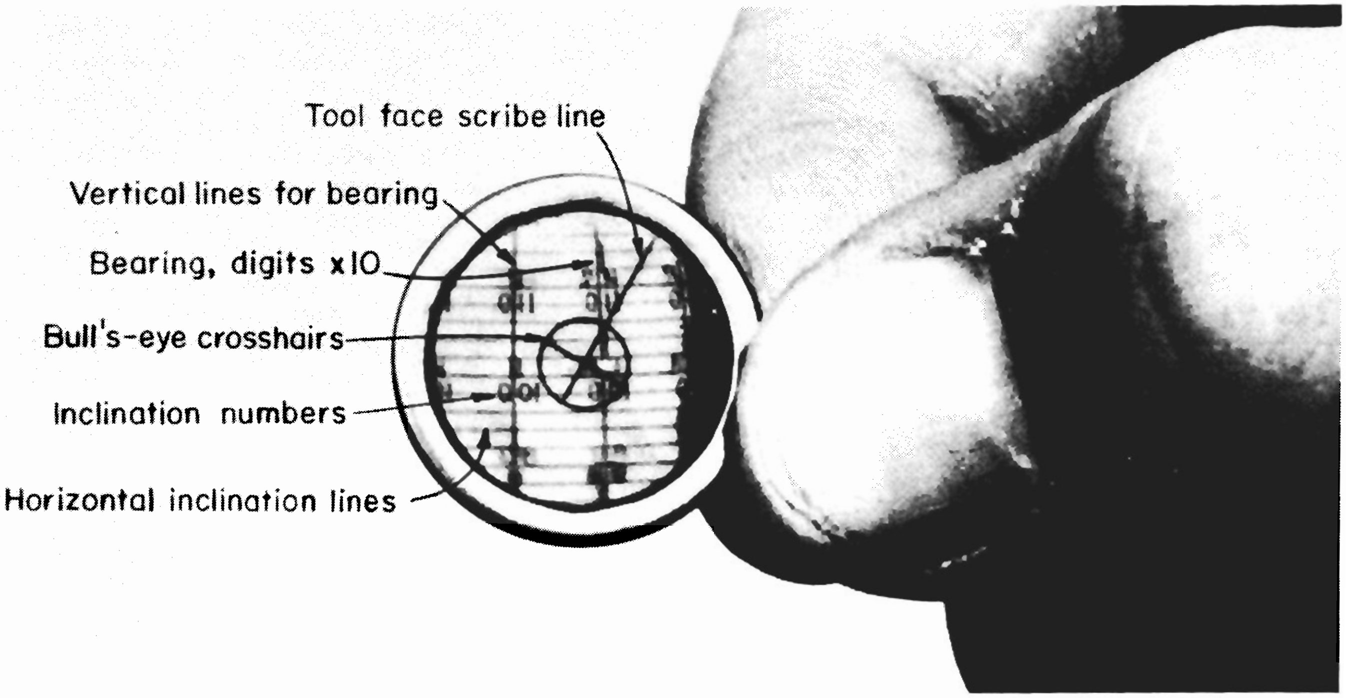


FIGURE 12.—Reading developed survey film disk.

SURVEYING ACCURACY

Directional drilling accuracy is primarily dependent on borehole surveying accuracy. Factors that influence borehole accuracy include inherent accuracy of the survey instrument, magnetic drill string interference, survey frequency or interval, and the calculation technique used to compute borehole coordinates and elevation.

The NL Sperry-Sun type B 120° directional single-shot survey instrument was used to monitor borehole inclination, bearing, and tool face orientation. The manufacturer's specified tolerance in measuring bearing for a recently calibrated compass (survey instrument) is ±0.5°. Furthermore, the resolution in reading the photographed compass bearing on the film disk is a random ±0.5°. Consequently, a potential error of ±1° exists in measuring borehole bearings using the subject survey instrument. The accuracy in surveying for inclination using the subject survey instrument is ±0.12°. Wolff and deWardt (8) state that, for a compass unit in good condition, a generally accepted systematic accuray is ±1°. Compass units measure magnetic north and require a declination correction to obtain true north. Wolff and deWardt suggest that declination corrections obtained from charts may be incorrect to ±0.5. The National Geophysical Data Center, Boulder, CO, or the U.S. Geological Survey, Reston, VA, can supply an accurate declination correction if provided with drill site (collar) coordinates and elevation. The declination correction at Navajo Dam drill site was 12° E ±13 min. Random misalignment of the survey hardware and instrument within the drill string with respect to the borehole is another possible source of error in borehole surveying for bearing and inclination (fig. 13). The magnitude of this source of error is difficult to determine; Wolff and deWardt (8) estimate it at approximately ±0.2 to ±0.5°.

Compass-type surveying instruments sense only the direction of the local magnetic field vector and therefore are subject to systematic drill string interference. To reduce drill string interference, compass-type survey instruments must be properly spaced inside adequate lengths of nonmagnetic drill collar (NMDC). The NMDC used to drill the demonstration borehole consisted of a nonmagnetic in-hole motor (nonmagnetic rotor and housing 12 ft in length, bearing package and bit made of magnetic material 2 ft in length) and 100 ft of NQ-size wireline nonmagnetic stainless steel drill rod. Previous Bureau experience in directional drilling long horizontal boreholes in coal for methane drainage has shown that compass spacing of 20 ft above the bottom end of 100 ft of NMDC sufficiently reduces drill string interference. NL Sperry-Sun has completed selection charts as guides for estimating compass spacing based on geographical location (horizontal component of the earth's magnetic field intensity varies with location), borehole inclination, and bearing, as indicated in figure 14 (9). Based on the selection chart shown for the Navajo Dam location, uncorrected bearing of N 10° W, and inclination of 90°, the compass should be located 20 ft from the bottom of the NMDC. While conducting a borehole survey, the NL Sperry-Sun single-shot was placed 13 ft from the bottom of the NMDC, or 16 ft from the

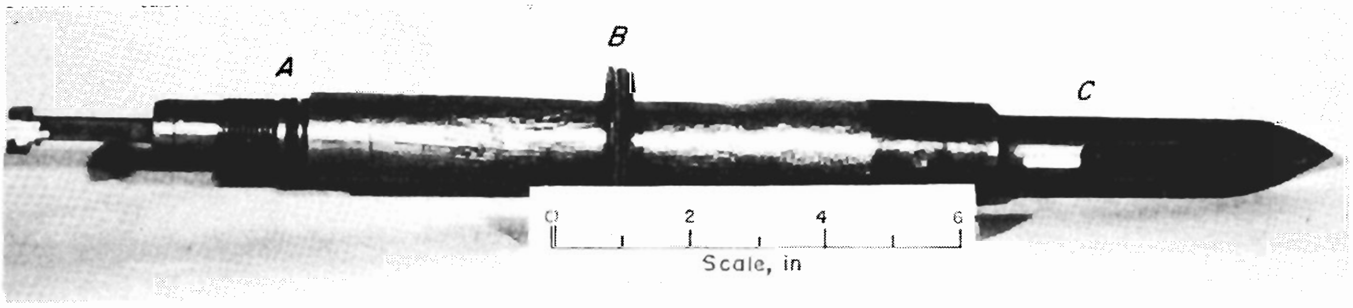


FIGURE 13.—Survey hardware. *A*, snubber; *B*, centralizing pumpdown washers; *C*, muleshoe.

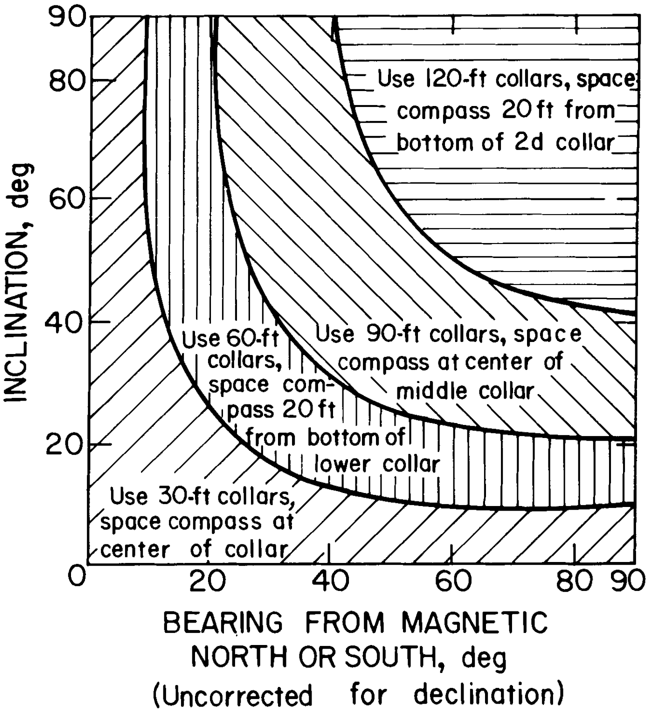


FIGURE 14.—Nonmagnetic drill collar and compass spacing selection chart.

bit. Although this spacing was 7 ft less than the estimated compass spacings, having the compass closer to the bit enhanced the accuray in projecting the current position of the bit from the survey position.

Two related factors that affect borehole surveying accuracy are surveying frequency and the surveying calculation technique used to determine borehole coordinates and elevation. It is generally accepted that regardless of calculation technique applied, short survey intervals will result in increased accuracy (10). Borehole surveys were conducted at 10-ft drilling intervals at Navajo Dam. Of the dozen or so surveying calculation techniques available, balanced tangential, radius of curvature, minimum curvature, and angle averaging are generally accepted as providing similar and acceptable results (10). A radius of curvature program adapted for a Hewlett Packard 15C calculator was used to calculate borehole coordinates and elevation. Angle averaging was used periodically to check the radius of curvature results.

PLANNING THE BOREHOLE

The borehole starting coordinates were N 19,567.69, E 52,697.69; elevation at the collar was 5,933.53 ft. The designated "punchout" was to occur within a 5-ft radius of N 20,447.31, E 52,709.41 at an elevation of 6,049.03 ft (figs. 15-16). The location of the borehole was determined after considering the geology of the right abutment and the constraints that specific geologic features would impose on the placement of the borehole. The abutment in the vicinity of the borehole consists predominantly of coarse-to-medium-grained sandstone with interbedded shale and siltstone (fig. 15). The sandstone is comprised mostly of very hard angular quartz grains weakly to moderately cemented having an unconfined compressive strength of less than 6,900 psi (4). The weak nature of the sandstone's intergranular material indicated that the rock would probably drill easily even though the sandstone's quartz grains were very hard and abrasive. Rock outcrops within the right abutment contain both vertical and horizontal joints. Unfortunately, the exact locations of the joints could not be determined because of thin soil cover, and thus the borehole trajectory could not be planned to avoid intercepting them. However, the borehole was designed to avoid intercepting the sand-filled joint shown in figure 15. The elevation at the bottom of the sand-filled joint was estimated to be 5,950 ft, or about 16.5 ft above the collar of the borehole. To prevent drilling into the joint, the first 250 ft of the demonstration borehole was to be drilled keeping borehole elevation near the elevation of the collar, or 5,933 ft. Drilling was to continue from 250 to 340 ft, by applying maximum build and tool face directions of 0° to 20° right and left (fig. 10). A desired increase in borehole inclination from 90.0° (horizontal inclination) to 101.0° (11.0° above horizontal) would result at 300 to 340 ft. Borehole inclination was then to be maintained at or near 101.0° to borehole completion in

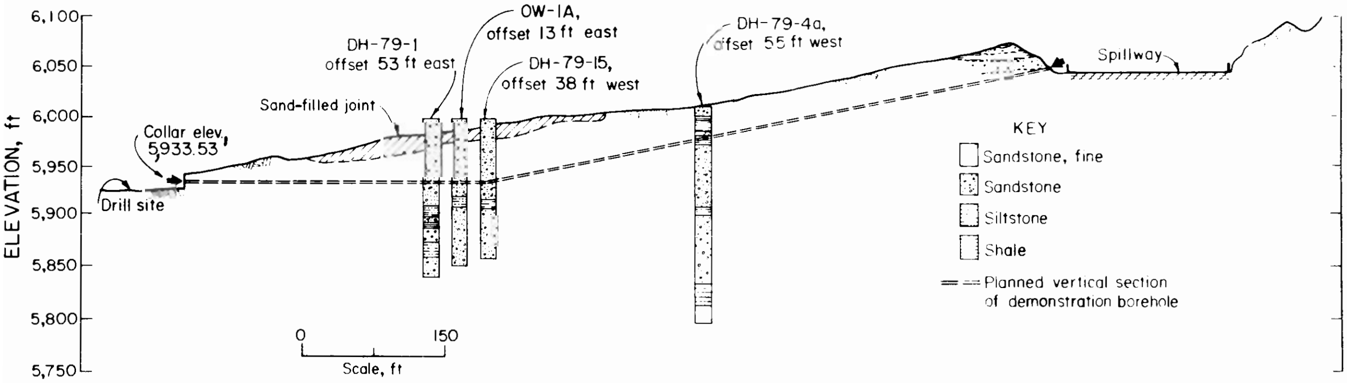


FIGURE 15.—Vertical section of planned demonstration borehole.

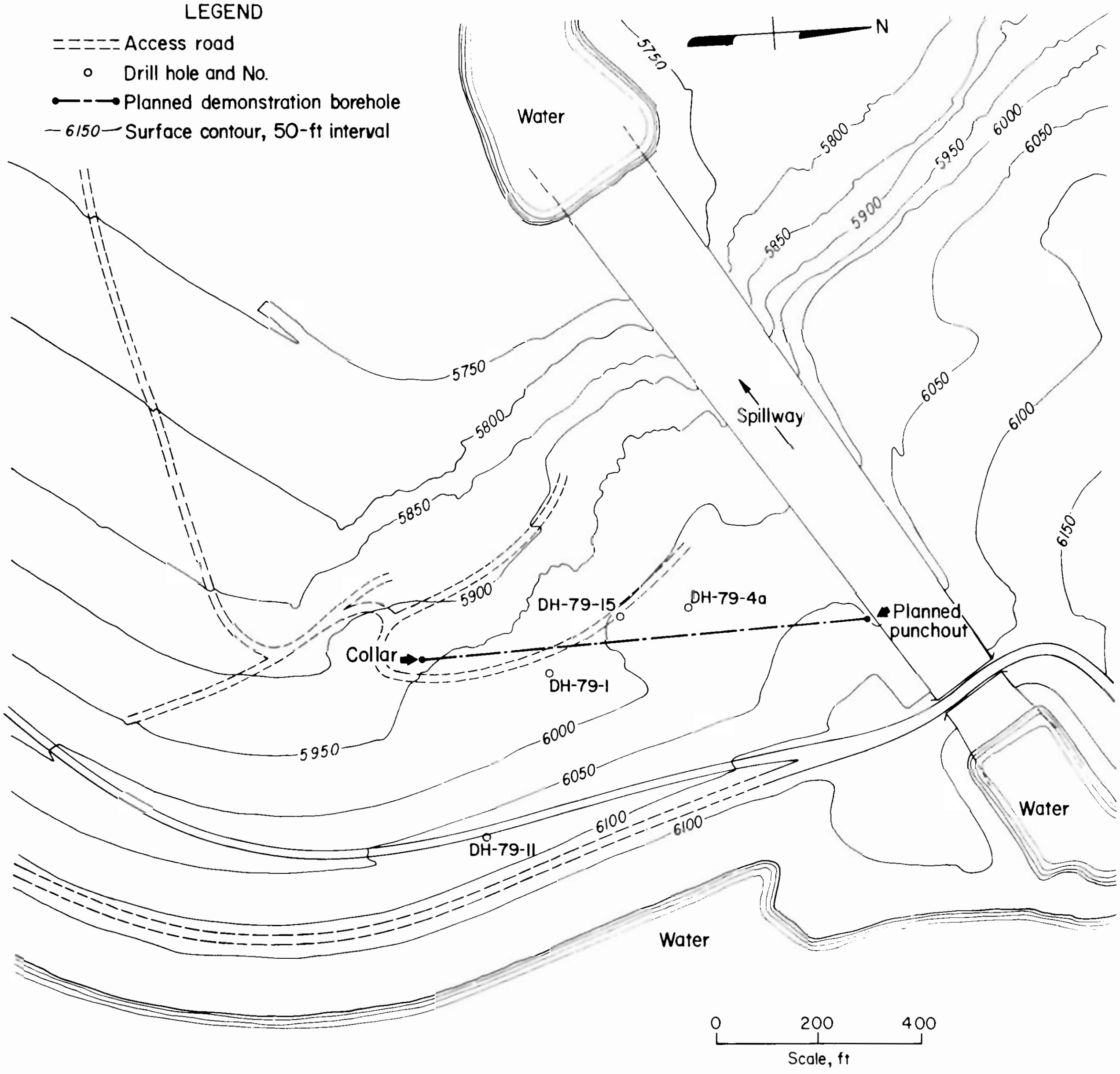


FIGURE 16.—Map view of planned demonstration borehole.

order to intercept the target elevation. While maintaining desired vertical trajectory as mentioned, an attempt was to be made to maintain departure within 2 ft east or west from the planned straight-line collar to punchout trajectory (fig. 16). The departure of the straight-line collar to punchout trajectory having a bearing of N 0°-45'-00" E was calculated and appears in appendix table A-2. This information would be used continuously during drilling to monitor deviation from the desired borehole departure.

DIRECTIONAL DRILLING THE DEMONSTRATION BOREHOLE

Several bent housings were used to drill the demonstration borehole; the 2° bent housing was the most effective in controlling vertical and horizontal trajectories (fig. 8). Before discussing the effectiveness of the bent housings, the drilling of the borehole's vertical and horizontal trajectories is briefly described.

The first 250 ft of the borehole were drilled maintaining elevation near the collar elevation as planned (fig. 17). Drilling continued to a depth of 495 ft without developing the necessary increase in vertical borehole trajectory. Consequently, the borehole was abandoned in order to start a new borehole within the initial borehole at a depth of 289 ft. After the new borehole was started at 289 ft, drilling continued to borehole completion at 885 ft, maintaining desired vertical trajectory.

Horizontal borehole trajectory during the first 250 ft of the borehole was maintained to within 2.5 ft of the desired departure. (Table A-2 gives the actual borehole survey log and desired borehole departures.) As drilling continued from 250 ft to 495 ft, horizontal borehole trajectory deviated from the desired course. After the new borehole was started at 289 ft, horizontal trajectory of the new borehole was maintained close to the desired course to borehole completion, according to borehole surveys (fig. 18).

EFFECTIVENESS IN CONTROLLING BOREHOLE TRAJECTORY

The 1/2° bent housing with pad was used to drill the initial borehole to a depth of 455 ft (fig. 19). Although the desired vertical and horizontal borehole

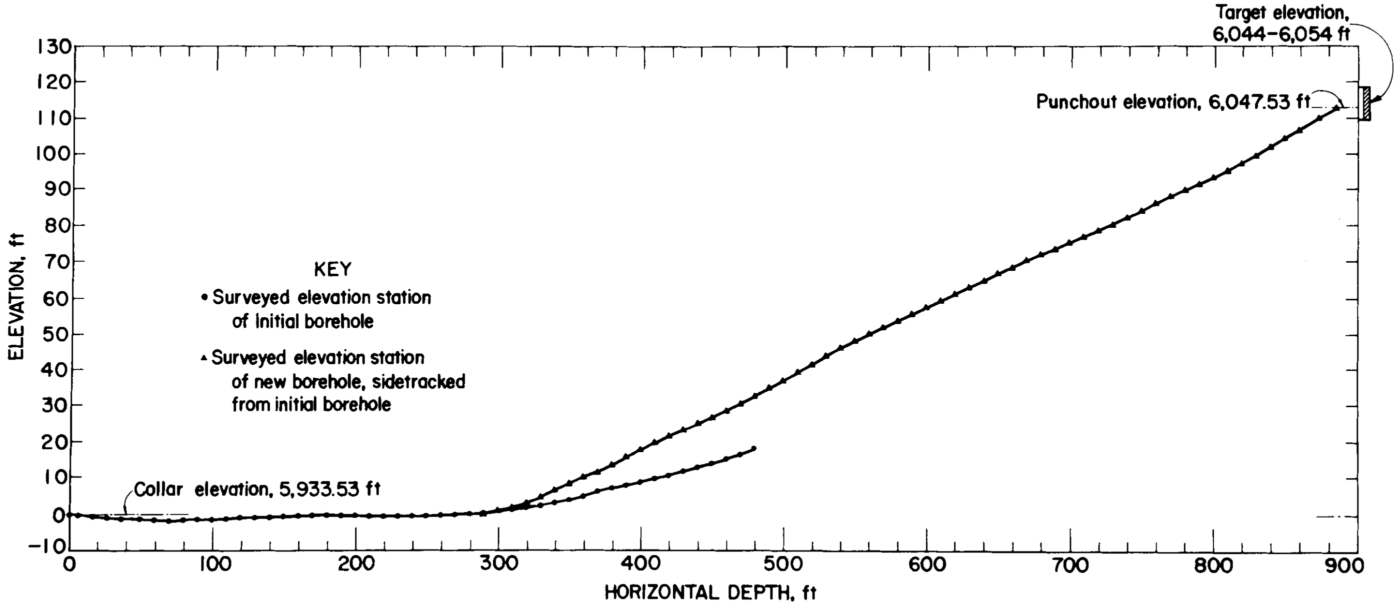


FIGURE 17.—Vertical section of demonstration borehole.

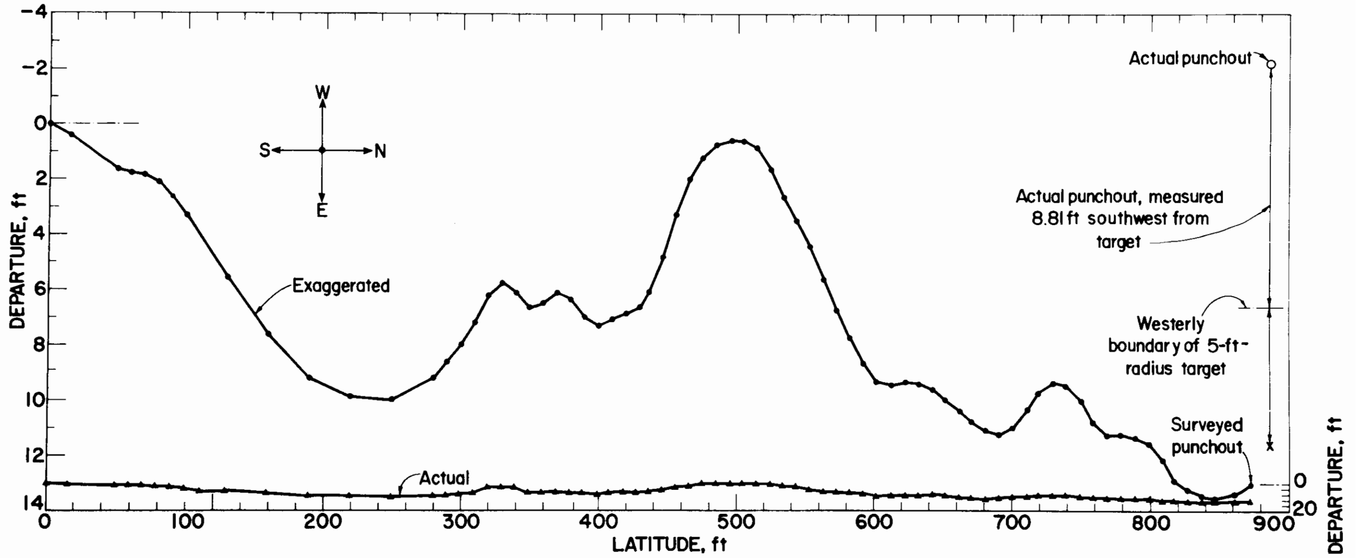


FIGURE 18.—Plan view of demonstration borehole. Abandoned borehole from 279 to 495 ft not shown. Before drilling of side-tracked borehole began at 289 ft, initial borehole resurveyed from 89 to 279 ft at 30-ft intervals as shown.

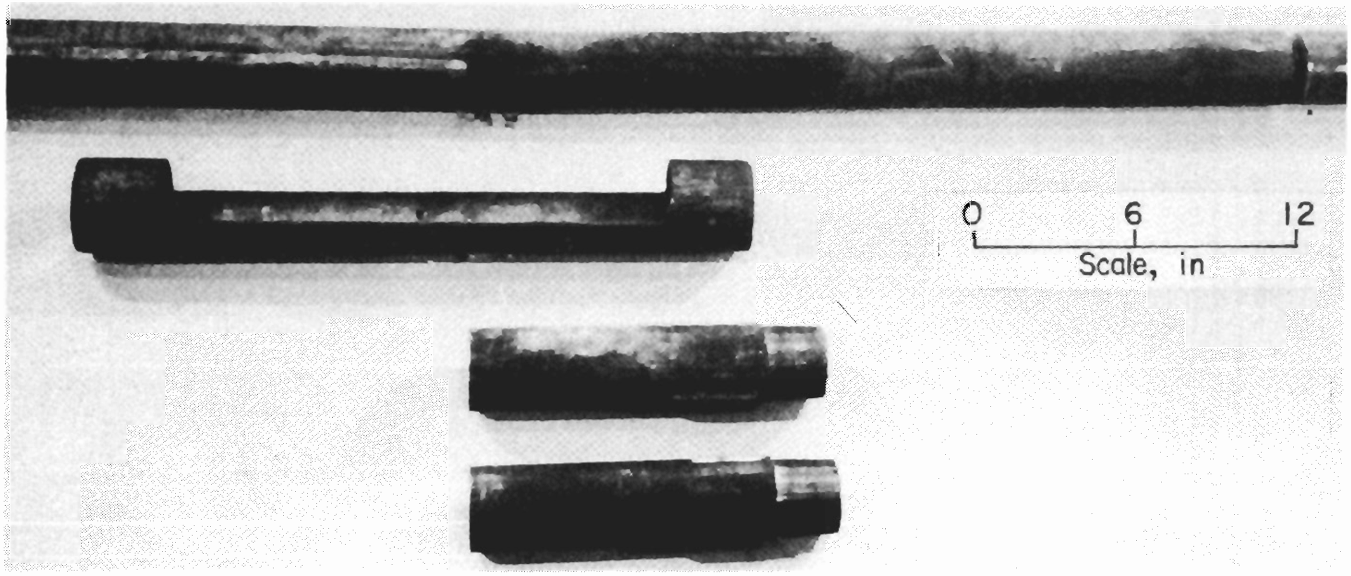


FIGURE 19.—Various bent housings. Top to bottom: 2° bent housing on in-hole motor, slip-on shoe, 1° bent housing with pad, 1/2° bent housing with pad.

trajectories were maintained to a depth of 250 ft, the vertical and horizontal deflection rates were inconsistent and unpredictable. Drilling continued to a depth of 455 ft without success in bringing the vertical and horizontal borehole trajectories to the desired course. The inconsistent deflection rates causing poor trajectory control resulted from a lack of sufficient side force being generated while using the 1/2° bent housing. The weak nature of the sandstone's intergranular material is believed to have negated any potential side force generated by the 1/2° bent housing. At a depth of 455 ft, the drill string and in-hole motor were pulled out of the borehole to replace the 1/2° housing with a 1° bent housing, after it became apparent that the necessary increase in elevation of 112 ft and change in departure of 14 ft east required to intercept the target could not be accomplished using the 1/2° bent housing.

Drilling continued from 455 ft to a depth of 495 ft using the 1° bent housing with pad (fig. 19). Even though the vertical deflection rates were more consistent when compared to the 1/2° bent housing, the horizontal borehole trajectory continued west instead of east. At the survey depth of 479 ft (bit depth of 495 ft), the borehole was calculated to be 16.8 ft west of the target departure and 96.0 ft below target elevation. Consequently, it was decided to abandon the borehole and to sidetrack or start a new borehole from within the initial borehole at a depth of 289 ft. As with the 1/2° bent housing, the 1° bent housing apparently failed to generate sufficient side force to control borehole trajectory.

To accommodate the sidetrack at a depth of 289 ft, enough drill rod was removed from the borehole to position the drill bit at a depth of 275 ft, to begin the sidetrack. The sidetracking procedure has been described in a previous Bureau of Mines publication (2). Using the in-hole motor equipped with the 1° bent housing, the sidetrack was started at a depth of 275 ft and completed at a borehole depth of 289 ft (fig. 17). The initial borehole was also resurveyed from 89 to 289 ft, primarily for bearing, after replacing a defective muleshoe and centralizing pumpdown washers that were believed to have caused error in measuring borehole bearing (table A-2, figure 13).

Drilling of the new borehole resumed from 289 ft to a depth of 385 ft after the 1° housing was replaced with a 2° housing equipped with a slip-on shoe (positioned on the in-hole motor at the apex of the 2° bent housing) (fig. 19). Desired borehole inclination and elevation were attained at a depth of 329 ft after only 40 ft of drilling with the 2° housing and slip-on shoe and were maintained thereafter. By referring to the actual borehole survey log and the desired borehole departures in table A-2, it can be seen that horizontal trajectory was returned to and controlled within 2 ft of the desired borehole departure (fig. 18). Control on both vertical and horizontal borehole trajectories was accomplished for the first time because the tool face settings resulted in predictable and consistent deflection rates. While drilling with the 2° housing and slip-on shoe, compared to the previous bent housings, the side force generated was great enough to overcome the weak nature of the sandstone's intergranular material. Although directional control had improved, the slip-on shoe frequently got stuck in the borehole while drilling, causing the average penetration rate to decrease to 7 in/min from 21 in/min with the previous housings. Therefore, at a depth of 385 ft, the drill rods and in-hole motor were removed from the borehole to remove the slip-on shoe from the 2° bent housing.

The demonstration borehole was completed to the final borehole depth of 885 ft using the 2° bent housing without the slip-on shoe (figures 8 and 19). Actual deflection rates were consistent and predictable for directional control with the 2° housing (table 1). The horizontal borehole trajectory was maintained within 2 ft east or west of the designed trajectory except for a short interval around 500 ft (fig. 18). Borehole elevation or vertical trajectory increased at an average rate of 1.98 ft per 10 ft drilled, maintaining an average borehole inclination of approximately 101.0° to successfully intercept the designated target elevation (fig. 17).

BOREHOLE PUNCHOUT AND INVESTIGATING ERROR IN AZIMUTH

The actual demonstration punchout depth was 885 ft at elevation 6,047.53, 1.50 ft below target center and 8.81 ft southwest of the target perimeter or 13.81 ft southwest of target center (fig. 20). The targeted punchout was to occur within a 5-ft radius with center coordinates of N 20,447.31, E 52,709.41 at elevation 6,049.03 ft. The calculations from the NL Sperry-Sun surveys showed the punchout

TABLE 1. - Measured deflection rates using 2° bent housing, degrees per foot

Tool face setting	Change in inclination (vertical)[1]		Change in bearing (horizontal)[2]	
	Range	Average	Range	Average
Right:				
20° to 40°.....	+0.09	+0.09	0.19R-0.27R	0.23R
40° to 60°.....	+0.00 to +.11	+.06	.02R- .41R	.15R
60° to 80°.....	+.01 to +.12	+.06	.08R- .36R	.19R
80° to 100°....	-.07 to +.08	-.01	.09R- .49R	.18R
100° to 120°...	-0.2 to -.06	-.04	NAp	.13R
120° to 140°...	-.07 to -.10	-.08	.01R- .13R	.07R
140° to 160°...	NAp	-.06	NAp	.03R
Left:				
0° to 20°[3].....	-.03 to +.09	-.03	.30L- .11R	.12L
40° to 60°.....	-.01 to +.06	+.05	.52L- .00R	.15L
60° to 80°.....	-.12 to +.06	-.02	.40L- .02L	.25L
80° to 100°....	-.12 to +.04	-.04	.13L- .59L	.36L
100° to 120°...	NAp	-.13	NAp	.07L
120° to 140°...	-.07 to -.20	-.12	.53L- .01R	.24L
140° to 160°...	NAp	-.16	NAp	.11R

NAp Not applicable.

[1] + Increase (buildup); - decrease (drop).

[2] R Right (east); L Left (west).

[3] Left tool face settings were applied from 805- to 885-ft borehole depth. During that drilling interval, the necessary bit thrust of >7,000 lb was not readily available. Consequently, drilling penetration rates and deflection magnitudes decreased.

to be at elevation 6,047.14 ft 1.89 ft below the target center, and at coordinates N 20,439.96, E 52,710.80, 1.4 ft northeast of the target center. The elevation error between the actual and calculated punchout was 0.39 ft, which was well within the accuracy of the survey instrument. The coordinate error between the actual and calculated punchout was 15.20 ft (figures 18 and 20), which was within the 1° accuracy of the survey instrument in measuring bearing.

Investigation into calculating systematic compass error caused by drill string interference has indicated that a possible error of 0.30° E was imposed on the compass (11). Applying the equation developed by Blythe and Callas (11) for estimating compass spacing,

$$C = \sin^{-1} ((F/H)(\sin (I) \sin (E))),$$

where C = compass correction, °,

F = net forces affecting compass, EMU,

H = horizontal component of earth's magnetic field intensity (23,300 nT or 0.0233 EMU at Navajo Dam, according to the National Geophysical Data Center),

I = borehole inclination, 95°,

and E = compass reading, 350°.

$$F = PL / (DL)^2 + PU / (DU)^2,$$

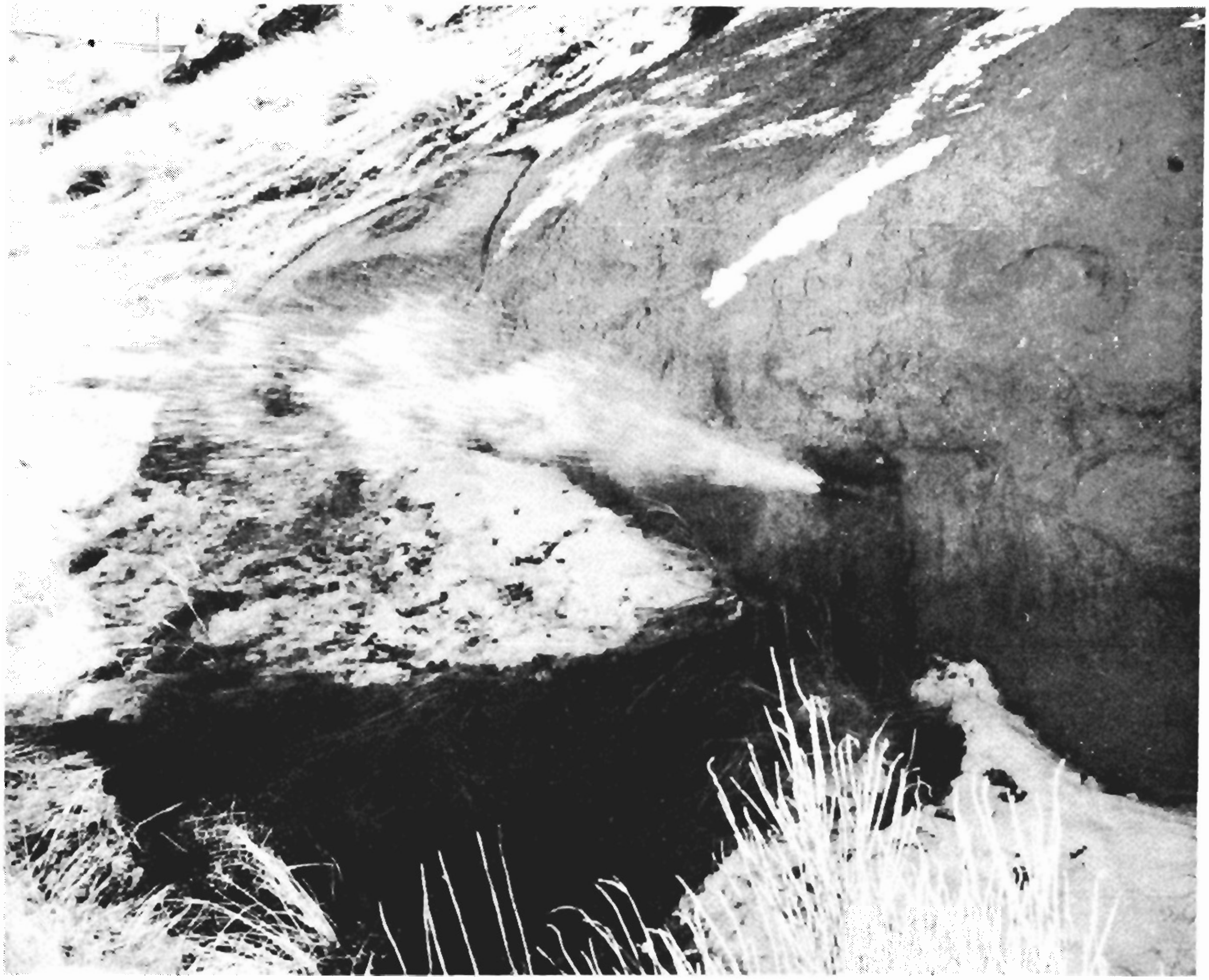


FIGURE 20.—Borehole punchout.

where PL = lower pole strength, estimated at 100 EMU,

PU = upper pole strength, estimated at 1,000 EMU,

DL = compass distance from lower pole, 400 cm,

and DU = compass distance from upper pole, 3,020 cm.

C = -0.30° (correction of 0.30° W).

A final punchout departure of 52,706.16 E was calculated by applying the compass error correction to the previously surveyed borehole bearings. This departure is 4.61 ft closer to the actual punchout as compared to not applying the compass correction. Although caution must be used when calculating compass correction caused by drill string interference, because pole strengths cannot be measured precisely and are not constant, the calculation in this application would have increased borehole punchout accuracy.

CONCLUSIONS

The demonstration borehole was directionally drilled to a final depth of 885 ft, where punchout occurred. Final borehole elevation was well within the target; borehole punchout coordinates were 8.81 ft southwest of the target. Boreholes can only be directionally drilled within the accuracy of the borehole survey system used. The NL Sperry-Sun type B 120° single-shot directional survey instrument is accurate to within 1° bearing and 0.24° inclination. The borehole-surveyed punchout, relative to the land-surveyed actual punchout, was within the accuracy of the NL Sperry-Sun survey instrument. The 2° bent housing was the most effective in maintaining directional control of the vertical and horizontal borehole trajectories.

As a result of the demonstrated borehole drilling accuracy, the original plan of constructing a long tunnel under the right abutment of Navajo Dam and drilling 150-ft boreholes from inside the tunnel to control water seepage was abandoned. The Bureau of Reclamation has instead contracted the construction of a shorter tunnel and the accurate drilling of boreholes as long as 600 ft, resulting in a substantial cost savings to the taxpayer.

REFERENCES

1. Oyler, D. C., and W. P. Diamond. Drilling a Horizontal Coalbed Methane Drainage System From a Directional Surface Borehole. BuMines RI 8640, 1982, 50 pp.
2. Kravits, S. J., A. Sainto, and G. L. Finfinger. Comparison of Rotary and In-Hole Motor Techniques for Drilling Horizontal Boreholes in Coal. BuMines RI 8933, 1985, 33 pp.
3. _____. The Advantages of In-Hole Motor Drilling. Coal Min., v. 21, No. 11, 1984, pp. 44-46.
4. Ehler, W. C. Final Report on Investigations for Seepage Control Navajo Dam. U.S. BuReclamation (Dep. Interior), 1983, 48 pp.
5. Pittard, F. High Torque 2-7/8-in-OD In-Hole Motor Performance Data. Slimdril Inc., Houston, TX, 1984, 21 pp.
6. American Petroleum Institute. Directional Drilling Survey Calculation Methods and Terminology. Bull. D20, Dec. 1985, 31 pp.
7. NL Sperry-Sun (Oklahoma City, OK). Magnetic Directional Single-shot Operating Instructions. 1972, 12 pp.
8. Wolff, C. J. M., and J. P. deWardt. Borehole Position Uncertainty Analysis of Measuring Methods and Derivation of Systematic Error Model. J. Pet. Technol., v. 33, 1981, pp. 2339-2350.
9. Blythe, E. J., Jr. Estimating Compass Spacing Inside Nonmagnetic Collars. Drilling - DCW, v. 36, 1975, pp. 44-47.
10. Fitchard, E. E. Randomly Simulated Borehole Tests Accuracy of Directional Survey Methods. Oil and Gas J., v. 79, No. 26, 1981, pp. 140-150.
11. Blythe, E. J., Jr., and N. P. Callas. Procedure Improves Platform Well Location Technique. Oil and Gas J., v. 75, No. 18, 1977, pp. 224-232.

APPENDIX.--DRILL AND BOREHOLE SURVEY LOGS

TABLE A-1. - Log of directional drilling parameters

Date, 1985	Borehole depth, ft	Intake water		Bit rotation, r/min	Bit torque, ft·lbf	Thrust pressure, bars	Thrust[1] force, lbf	Drill time, 10-ft rod, min	Survey time, min	Comments
		gpm	psig							
Sept.:										
19....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	3-1/2-in reamed to 6-in ID.
Oct.:										
4....	45	70	550	855	95	125	2,330	9		
4....	55	70	550	855	95	125	2,330	5		
7....	65	70	550	855	95	125	2,330	5		
7....	75	70	550	855	95	125	2,330	11		
8....	85	70	550	855	95	125	2,330	10		
11....	95	70	550	855	95	125	2,330	10		
19....	105	65	600	785	110	125	2,330	8		
19....	115	65	600	785	110	125	2,330	8		
20....	125	65	550	785	95	210	3,914	6		Lost circulation.
20....	135	65	550	785	95	215	4,008	7	56	
20....	145	65	550	785	95	250	4,660	12	30	
20....	155	65	550	785	95	250	4,660	10	28	Completed dye test.
22....	165	65	600	785	110	240	4,474	7	41	Regained circulation.
22....	175	65	550	785	95	225	4,194	7	41	
22....	185	65	550	785	95	220	4,100	11	51	
22....	195	65	550	785	95	235	4,380	10	43	
23....	205	65	550	785	95	235	4,380	8	32	
23....	215	65	550	785	95	235	4,380	8	41	
23....	225	65	550	785	95	245	4,567	7	45	Lost partial circulation.
23....	235	65	550	785	95	232	4,324	9	31	Do.
23....	245	65	550	785	95	230	4,287	8	25	Do.
23....	255	65	575	785	100	235	4,380	6	54	Do.
23....	265	65	575	785	100	240	4,474	4	47	Do.
23....	275	65	575	785	100	240	4,474	3	13	Do.
23....	285	65	550	785	95	240	4,474	3	24	Do.
24....	295	66	700	800	125	245	4,567	3	24	Do.
24....	305	65	625	785	110	248	4,622	4	30	Do.
24....	315	65	575	785	100	250	4,660	4	45	Do.
24....	325	68	575	825	100	250	4,660	3	26	Return water flow increased.
24....	335	67	575	813	100	248	4,622	4	34	Do.
24....	345	68	575	825	100	245	4,567	3	90	Do.

NAp Not applicable. [1] Thrust force = Thrust pressure (bars) × 14.7 psig/bar × 1.268 in^2 (piston area).

TABLE A-1. - Log of directional drilling parameters--Continued

Date, 1985	Borehole depth, ft	Intake water		Bit rotation, r/min	Bit torque, ft·lbf	Thrust pressure, bars	Thrust[1] force, lbf	Drill time, 10-ft rod, min	Survey time, min	Comments
		gpm	psig							
Oct.:										
24....	355	67	600	813	110	245	4,567	3	31	Return water flow increased.
24....	365	67	600	813	110	245	4,567	4	33	Output flow exceeded input.
25....	375	67	600	813	110	235	4,380	3	139	Output flow >70 gpm.
25....	385	67	600	813	110	245	4,567	4	57	
25....	395	67	575	813	100	250	4,660	4	49	
25....	405	67	500	813	90	255	4,753	4	50	
25....	415	65	550	785	95	255	4,753	5	35	
25....	425	65	500	785	90	250	4,660	6	67	
25....	435	68	550	825	95	250	4,660	3	31	
25....	445	68	625	825	110	250	4,660	3	40	80-gpm outflow.
25....	455	68	625	825	110	250	4,660	4	31	
26....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	Installed 1° housing.
30....	465	63	650	746	115	250	4,660	3	42	
30....	475	62	600	730	110	250	4,660	3	39	
30....	485	62	700	730	125	250	4,660	3	31	
30....	495	68	700	825	125	250	4,660	3	36	
Nov.:										
1....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	Sidetracked at 289 ft.
4....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	Installed 2° with shoe.
5....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	Surveying problems.
6....	305	65	650	785	170	250	4,660	21	32	100-gpm output.
6....	315	66	650	800	176	250	4,660	28	47	
6....	325	67	650	813	178	250	4,660	13	19	
7....	335	66	650	800	176	230	4,287	9	30	
7....	345	66	550	800	176	250	4,660	13	30	
7....	355	65	600	785	156	260	4,846	8	21	
7....	365	69	600	839	166	250	4,660	31	32	
7....	375	65	600	785	156	250	4,660	21	32	
8....	385	67	550	813	148	260	4,846	25	30	
8....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	Removed slip-on shoe.
9....	395	68	500	825	90	260	4,846	5	23	
9....	405	66	525	800	90	275	5,126	5	42	
9....	415	65	550	785	95	295	5,499	4	28	
9....	425	66	500	800	90	290	5,406	5	45	
9....	435	65	550	785	95	305	5,685	6	59	Conducted 2 surveys.
9....	445	66	510	800	90	300	5,592	5	22	
9....	455	67	510	813	90	295	5,499	5	26	
9....	465	66	600	800	110	310	5,778	6	19	
9....	475	66	550	800	95	300	5,592	5	22	

11....	485	66	550	800	95	300	5,592	6	90	Surveying problems.
11....	495	65	600	785	110	300	5,592	4	59	Conducted 2 surveys.
11....	505	65	575	785	100	300	5,592	7	62	Do.
11....	515	64	525	771	90	300	5,592	5	22	
11....	525	65	550	785	95	310	5,778	8	69	Do.
11....	535	65	550	785	95	310	5,778	7	44	
11....	545	65	525	785	90	320	5,965	6	30	
12....	555	66	550	800	95	320	5,965	11	50	Do.
13....	565	67	470	813	75	310	5,778	6	31	
13....	575	67	490	813	90	310	5,778	6	20	
13....	585	65	525	785	90	310	5,778	6	45	
13....	595	64	550	771	95	310	5,778	5	46	
14....	605	67	525	813	95	320	5,965	9	30	
14....	615	65	540	785	95	320	5,965	11	15	
14....	625	66	550	800	95	320	5,965	10	28	
14....	635	66	490	800	90	320	5,965	9	67	Do.
14....	645	65	520	785	90	320	5,965	6	22	
14....	655	65	550	785	95	320	5,965	6	29	
14....	665	66	500	800	90	320	5,965	7	35	
15....	675	66	500	800	90	320	5,965	15	21	
15....	685	66	500	800	90	320	5,965	7	155	Repaired survey hardware.
15....	695	65	575	785	100	320	5,965	15	25	
15....	705	67	525	813	90	320	5,965	9	30	
15....	715	67	500	813	90	320	5,965	6	17	
15....	725	67	500	813	90	320	5,965	8	21	
16....	735	66	500	800	90	320	5,965	17	20	
16....	745	66	500	800	90	320	5,965	23	25	
16....	755	66	470	800	85	320	5,965	25	29	
16....	765	65	495	785	90	300	5,592	39	50	
16....	775	66	450	800	80	320	5,965	23	52	Used a winch, +1,000 lb.
16....	785	67	450	813	80	320	5,965	20	20	Do.
16....	795	65	480	785	85	320	5,965	20	30	Do.
18....	805	65	425	785	75	320	5,965	16	27	Do.
18....	815	66	475	800	80	320	5,965	15	21	Do.
18....	825	66	500	800	90	320	5,965	13	27	Do.
18....	835	66	500	800	90	320	5,965	11	30	Do.
18....	845	66	480	800	80	320	5,965	11	33	Do.
18....	855	65	470	785	80	320	5,965	13	22	Do.
18....	865	65	450	785	75	320	5,965	12	26	Do.
18....	875	65	460	785	75	320	5,965	14	33	Do.
18....	885	65	470	785	80	320	5,965	11	27	Do.

NAp Not applicable. [1] Thrust force = Thrust pressure (bars) × 14.7 psig/bar × 1.268 in^2 (piston area).

TABLE A-2. - Demonstration borehole survey log and log of desired departures

Borehole depth, ft	Survey depth, ft	Borehole inclination, deg	Azimuth (uncorrected), deg[1]	Change in departures, ft	Change in latitudes, ft	Change in true vertical depth, ft	Departure, ft	Latitude, ft	True vertical depth, ft[2]	Desired departures, ft[3]	Corresponding depth, ft[4]
NAp	0	90.0	NAp	NAp	NAp	NAp	52,697.79	19,567.69	-5,933.53	52,697.79	0
NAp	6	87.9	NAp	NAp	NAp	0.11	NAp	NAp	-5,933.42	52,697.42	10
NAp	16	88.0	350.81	0.39	15.99	.36	52,698.18	19,583.68	-5,933.06	52,698.06	20
NAp	26	87.5	NAp	NAp	NAp	.39	NAp	NAp	-5,932.67	52,698.19	30
NAp	36	88.9	NAp	NAp	NAp	.31	NAp	NAp	-5,932.36	52,698.32	40
65	49	88.9	349.50	1.24	32.96	.19	52,699.42	19,616.64	-5,932.17	52,698.45	50
75	59	89.5	348.25	.15	9.99	.14	52,699.57	19,626.64	-5,932.03	52,690.58	60
85	69	90.0	348.50	.06	9.99	.04	52,699.64	19,636.64	-5,931.99	52,698.72	70
95	79	90.4	350.50	.26	9.99	-.03	52,699.90	19,646.63	-5,932.02	52,698.85	80
105	89	90.9	351.50	.52	9.98	-.11	52,700.42	19,656.62	-5,932.14	52,698.98	90
115	99	91.0	352.86	.73	9.97	-.17	52,701.15	19,666.59	-5,932.30	52,699.11	100
125	109	91.4	350.70	.66	9.97	-.21	52,701.81	19,676.57	-5,932.51	52,699.25	110
135	119	91.0	351.20	.51	9.98	-.21	52,702.33	19,686.55	-5,932.72	52,699.38	120
145	129	90.5	351.00	.54	9.98	-.13	52,702.87	19,696.54	-5,932.85	52,699.51	130
155	139	90.6	348.90	.31	9.99	-.10	52,703.18	19,706.53	-5,932.95	52,699.64	140
165	149	90.7	349.50	.17	9.99	-.11	52,703.35	19,716.53	-5,933.06	52,699.78	150
175	159	91.0	348.47	.17	9.99	-.15	52,703.52	19,726.53	-5,933.21	52,699.91	160
185	169	91.5	350.36	.25	9.99	-.22	52,703.77	19,736.52	-5,933.43	52,700.04	170
195	179	89.7	347.70	.18	9.99	-.10	52,703.95	19,746.52	-5,933.53	52,700.17	180
205	189	89.2	347.90	-.03	9.99	.10	52,703.91	19,756.52	-5,933.44	52,700.30	190
215	199	89.5	348.40	.03	9.99	.11	52,703.94	19,766.52	-5,933.33	52,700.44	200
225	209	89.9	348.70	.10	9.99	.05	52,704.04	19,776.51	-5,933.27	52,700.57	210
235	219	90.0	348.00	.06	9.99	.01	52,704.10	19,736.51	-5,933.26	52,700.70	220
245	229	90.1	345.70	-.20	9.99	-.01	52,703.90	19,796.51	-5,933.27	52,700.83	230
255	239	90.0	347.00	-.29	9.99	-.01	52,703.61	19,806.51	-5,933.28	52,700.96	240
265	249	90.0	345.50	-.31	9.99	.00	52,703.30	19,816.50	-5,933.28	52,701.10	250
275	259	90.5	346.30	-.37	9.99	-.04	52,702.94	19,826.50	-5,933.32	52,701.23	260
285	269	91.1	344.80	-.43	9.99	-.14	52,702.51	19,836.48	-5,933.46	52,701.36	270

295	279	91.6	345.35	-0.51	9.98	-0.24	52,702.00	19,846.47	-5,933.71	52,701.49	280
305	289	92.1	347.10	.31	9.99	-.33	52,701.69	19,856.46	-5,934.04	52,701.62	290
315	299	92.5	346.00	-.25	9.99	-.40	52,701.43	19,866.44	-5,934.44	52,701.75	300
325	309	93.0	345.35	-.41	9.98	-.48	52,701.03	19,876.42	-5,934.92	52,701.88	310
335	319	93.5	345.10	-.48	9.97	-.57	52,700.54	19,886.40	-5,935.49	52,702.01	320
345	329	93.9	345.10	-.50	9.97	-.65	52,700.04	19,896.36	-5,936.13	52,702.14	330
355	339	94.3	344.95	-.52	9.96	-.72	52,699.52	19,906.32	-5,936.85	52,702.27	340
365	349	94.9	345.10	-.52	9.95	-.80	52,699.01	19,916.28	-5,937.65	52,702.40	350
375	359	98.0	344.95	-.52	9.92	-1.12	52,698.49	19,926.20	-5,938.77	52,702.53	360
385	369	95.5	342.55	-.74	9.90	-1.18	52,697.75	19,936.10	-5,939.95	52,702.66	370
395	379	94.9	345.61	-.68	9.93	-.91	52,697.07	19,946.03	-5,940.86	52,702.79	380
405	389	94.8	347.01	-.29	9.95	-.85	52,696.78	19,955.99	-5,941.70	52,702.92	390
415	399	95.1	347.34	-.14	9.96	-.86	52,696.63	19,965.95	-5,942.57	52,708.05	400
425	409	95.6	346.94	-.15	9.96	-.93	52,696.48	19,975.91	-5,943.50	52,703.18	410
435	419	96.0	346.54	-.22	9.95	-1.01	52,696.26	19,985.85	-5,944.51	52,703.51	420
445	429	96.5	345.08	-.38	9.93	-1.09	52,695.89	19,995.79	-5,945.60	52,703.44	430
455	439	96.8	345.34	-.48	9.92	-1.16	52,695.40	20,005.71	-5,946.75	52,703.57	440
465	449	96.8	344.41	-.54	9.91	-1.18	52,694.86	20,056.62	-5,947.94	52,703.70	450
475	459	97.5	343.62	-.69	9.90	-1.24	52,694.17	20,025.52	-5,949.18	52,703.83	460
485	469	98.2	343.48	-.77	9.88	-1.37	52,693.40	20,035.40	-5,950.55	52,703.96	470
495	479	99.6	342.55	-.85	9.84	-1.55	52,692.54	20,045.24	-5,952.10	52,704.09	480
(5)	89	90.9	351.50	NAp	NAp	NAp	52,700.42	19,656.62	-5,932.14	52,698.98	90
(5)	99	91.0	352.50	.70	9.97	-.17	52,701.12	19,666.59	-5,932.31	52,699.11	100
(5)	129	90.9	352.00	2.22	29.91	-.50	52,703.34	19,696.51	-5,932.80	52,699.51	130
(5)	159	90.7	352.00	2.09	29.92	-.42	52,705.43	19,726.43	-5,933.22	52,699.91	160
(5)	189	89.2	350.00	1.57	29.96	.03	52,707.00	19,756.39	-5,933.20	52,700.30	190
(5)	219	90.0	348.50	.65	29.99	.21	52,707.66	19,786.38	-5,932.99	52,700.70	220
(5)	249	90.5	348.00	.13	29.99	.13	52,707.79	19,816.38	-5,933.12	52,701.10	250
(5)	279	91.7	345.00	-.78	29.98	-.58	52,707.00	19,646.36	-5,933.70	52,701.49	280
305	289	92.2	344.40	-.58	9.98	-.34	52,706.43	19,856.34	-5,934.04	52,701.62	290
315	299	93.9	344.50	-.62	9.97	-.53	52,705.81	19,866.30	-5,934.57	52,701.57	300
325	309	96.2	342.00	-.83	9.93	-.88	52,704.99	19,876.23	-5,935.45	52,701.88	310
335	319	98.9	342.70	-.98	9.86	-1.31	52,704.01	19,886.09	-5,936.76	52,702.01	320

See footnotes at end of table.

TABLE A-2. - Demonstration borehole survey log and log of desired departures--Continued

Borehole depth, ft	Survey depth, ft	Borehole inclination, deg	Azimuth (uncorrected), deg[1]	Change in departures, ft	Change in latitudes, ft	Change in true vertical depth, ft	Departure, ft	Latitude, ft	True vertical depth, ft[2]	Desired departures, ft[3]	Corresponding depth, ft[4]
345	329	100.9	347.90	-0.46	9.81	-1.72	52,703.55	19,895.93	-5,938.48	52,702.14	330
355	339	100.4	352.55	.38	9.82	-1.85	52,703.93	19,905.75	-5,940.33	52,702.27	340
365	349	99.9	349.60	.53	9.83	-1.76	52,704.46	19,915.58	-5,942.09	52,702.40	350
375	359	98.2	344.40	-.17	9.87	-1.57	52,704.29	19,925.45	-5,943.67	52,702.53	360
385	369	100.3	347.50	-.35	9.86	-1.61	52,703.93	19,935.31	-5,945.27	52,702.66	370
395	379	103.5	351.20	.23	9.78	-2.06	52,704.16	19,945.09	-5,947.34	52,702.79	380
405	389	102.9	352.50	.65	9.71	-2.28	52,704.82	19,954.80	-5,949.62	52,702.92	390
415	399	100.9	346.70	.27	9.78	-2.06	52,705.09	19,964.58	-5,951.68	52,703.05	400
425	409	101.0	346.70	-.22	9.81	-1.90	52,704.87	19,974.39	-5,953.58	52,703.18	410
435	419	100.0	346.80	-.21	9.83	-1.83	52,704.65	19,984.22	-5,955.41	52,703.31	420
445	429	100.0	346.50	-.23	9.84	-1.75	52,704.42	19,994.07	-5,952.14	52,703.44	430
455	439	100.0	343.30	-.53	9.83	-1.74	52,703.89	20,003.90	-5,958.89	52,703.57	440
465	449	100.4	338.14	-1.25	9.76	-1.77	52,702.64	20,013.66	-5,960.64	52,703.70	450
475	459	101.3	340.00	-1.52	9.70	-1.88	52,701.11	20,023.36	-5,962.53	52,703.83	460
485	469	101.9	341.20	-1.26	9.71	-2.01	52,699.85	20,033.07	-5,964.54	52,703.96	470
495	479	103.1	344.80	-.85	9.72	-2.16	52,699.00	20,042.80	-5,966.71	52,704.09	480
505	489	102.8	346.30	-.42	9.74	-2.24	52,689.58	20,052.53	-5,968.95	52,704.22	490
515	499	102.1	347.60	-.18	9.76	-2.16	52,698.40	20,062.30	-5,971.10	52,704.35	500
525	509	102.9	348.70	.03	9.76	-2.16	52,698.43	20,072.06	-5,973.26	52,704.48	510
535	519	103.5	350.00	.23	9.73	-2.28	52,698.65	20,081.80	-5,975.55	52,705.61	520
545	529	103.5	354.90	.75	9.69	-2.33	52,699.41	20,091.49	-5,977.88	52,705.74	530
555	539	102.5	353.30	1.04	9.69	-2.25	52,700.44	20,101.18	-5,980.13	52,705.87	540
565	549	100.9	352.20	.81	9.76	-2.03	52,701.26	20,110.93	-5,982.16	52,706.00	550
575	559	101.0	355.00	.96	9.77	-1.90	52,702.22	20,120.70	-5,984.06	52,706.13	560
585	569	100.3	355.10	1.21	9.75	-1.85	52,703.42	20,130.46	-5,985.91	52,706.26	570
595	579	100.7	353.80	1.10	9.77	-1.82	52,704.52	20,140.23	-5,987.73	52,706.39	580
605	589	100.8	353.80	.99	9.77	-1.87	52,705.52	20,150.00	-5,989.60	52,706.52	590
615	599	101.4	353.20	.94	9.77	-1.93	52,706.46	20,159.77	-5,991.52	52,706.65	600
625	609	101.0	350.50	.66	9.79	-1.94	52,707.12	20,169.56	-5,993.46	52,706.78	610

635	619	100.5	347.00	0.13	9.82	-1.86	52,707.24	20,179.38	-5,955.33	52,706.91	620
645	629	100.2	347.90	-.09	9.84	-1.80	52,707.15	20,189.21	-5,997.12	52,707.04	630
655	639	100.8	348.70	.05	9.83	-1.82	52,707.20	20,199.05	-5,998.95	52,707.17	640
665	649	101.5	349.80	.21	9.81	-1.93	52,707.42	20,208.85	-6,000.88	52,707.30	650
675	659	100.9	350.10	.33	9.80	-1.94	52,707.75	20,218.67	-6,002.82	52,707.43	660
685	669	100.2	350.70	.41	9.82	-1.83	52,708.16	20,228.48	-6,004.65	52,707.56	670
595	679	98.9	350.00	.40	9.80	-1.66	52,078.57	20,238.33	-6,006.31	52,707.69	680
705	689	99.5	349.50	.30	9.87	-1.60	52,708.87	20,248.20	-6,007.91	52,707.82	690
715	699	100.1	348.40	.16	9.85	-1.70	52,709.03	20,258.05	-6,009.61	52,707.95	700
725	709	98.9	344.40	-.28	9.86	-1.65	52,708.76	20,267.91	-6,011.26	52,708.08	710
735	719	99.5	344.20	-.64	9.85	-1.60	52,708.12	20,277.76	-6,012.86	52,708.21	720
745	729	100.1	345.00	-.58	9.84	-1.70	52,707.53	20,287.60	-6,014.56	52,708.34	730
755	739	101.0	346.50	-.38	9.82	-1.83	52,707.15	20,297.42	-6,016.39	52,708.47	740
765	749	102.1	350.60	.09	9.79	-2.00	52,707.24	20,307.22	-6,018.40	52,708.60	750
775	759	101.4	352.10	.57	9.77	-2.04	52,707.81	20,316.99	-6,020.43	52,708.73	760
785	769	101.2	353.40	.81	9.77	-1.96	52,708.63	20,326.76	-6,022.39	52,708.86	770
795	779	100.0	347.50	.42	9.82	-1.84	52,709.05	20,336.58	-6,024.23	52,708.99	780
805	789	100.1	348.40	.00	9.84	-1.74	52,709.04	20,346.42	-6,025.98	52,709.12	790
815	799	100.1	348.60	-.09	9.84	-1.75	52,709.13	20,356.27	-6,027.73	52,709.25	800
825	809	101.2	350.10	.23	9.82	-1.85	52,709.37	20,366.09	-6,029.58	52,709.38	810
835	819	102.2	352.80	.59	9.77	-2.03	52,709.45	20,375.86	-6,031.61	52,709.51	820
845	829	103.1	351.60	.71	9.73	-2.19	52,710.60	20,385.60	-6,033.80	52,709.64	830
855	839	103.3	348.60	.36	9.73	-2.20	52,711.02	20,395.32	-6,036.08	52,709.77	840
865	849	103.8	349.70	.19	9.72	-2.34	52,711.22	20,405.04	-6,038.42	52,709.90	850
875	859	104.1	347.50	.10	9.70	-2.41	52,711.32	20,414.75	-6,040.83	52,710.03	860
885	869	104.1	347.00	-.18	3.68	-3.41	52,711.14	20,428.32	-6,044.24	52,710.16	870
885	885	103.8	345.60	-.35	1.64	-2.89	52,710.80	20,439.96	-6,047.14	52,710.29	880

NAp Not applicable.

[1] Borehole bearing converted to uncorrected azimuth, radius of curvature calculator program. Corrects for magnetic declination (Navajo Dam, add 12° E in NE quadrant). Engineering 40 scale used to eliminate reader bias.

[2] Changes to TVD: Up -, Down +.

[3] Log of desired departures every 10 ft, collar to 880 ft using azimuth of 0.76°.

[4] Depth at which desired departures calculated.

[5] Borehole terminated at 495 ft, new borehole sidetracked at 289 ft. Borehole resurveyed 89 to 279 ft because of defective survey hardware; used original surveys 0 to 89 ft.

U.S. GOVERNMENT PRINTING OFFICE: 1987 · 605-017/60063

INT.-BU.OF MINES,PGH.,PA. 28518