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DEMONSTRATION OF ACCURATE DIRECTIONAL DRILLING AT NAVAJO DAM

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UNIT OF MEASURE ABBREVIATIONS

a-c	alternating current (adj.)
emu	electromagnetic unit
ft	foot
ft-lbf	foot pound (force)
gal	gallon
gpm	gallons per minute
hp	horsepower
in	inch
in/min	inches per minute
lbf	pounds force
lb/in^2 (gauge)	pounds per square inch, gauge
min	minute
r/min	revolution per minute
V	volt

DEMONSTRATION OF ACCURATE DIRECTIONAL DRILLING AT NAVAJO DAM

INTRODUCTION

To demonstrate the accuracy of directional drilling, the Bureau of Mines was requested to drill three near-horizontal boreholes at Navajo Dam, Colorado River Storage Project, New Mexico. The objectives of this program were to intercept a designated target, to determine the feasibility of accurately drilling long (1,000 feet) horizontal borings, and to evaluate the effect of horizontally drilled drains on the control of seepage.

Due to monetary and other constraints, only one of the three near-horizontal borings was drilled. The two additional borings that were to be drilled from the right abutment to the centerline of the embankment will be drilled as part of the contract for right abutment seepage control modifications. As a consequence, the effect of horizontally drilled borings for seepage control below the embankment was not thoroughly determined.

The oil and gas industry has applied directional drilling techniques for the past decade to drill exploration wells, multiple completion wells, and for well blowout control. Exploration wells have been directionally drilled when surface access was not available, due to unfavorable topography or lack of surface ownership. Directional drilling has been widely used to drill multiple production wells from a single vertical well, enhancing the rate of recovery of the commodity being produced. Accurate directional drilling has been used for intercepting excessively high pressure oil wells that have suffered blowouts due to the failure of surface control systems.

The pipeline crossing industry has applied directional drilling techniques for accurate drilling under rivers to provide access for utilities. Proven advantages of directional drilling for river crossings include: uninterrupted river traffic; minimal maintenance of pipeline crossings; elimination of ecological damage to the river; minimal right-of-way requirements; reduced completion time; and lower costs [1,2].[1]

Accurate directional drilling has been researched and demonstrated by the Bureau of Mines as part of its methane control program [3,4,5]. In 1979, using a downhole motor, a directional borehole was drilled from the surface to a measured depth of 1,595 feet, maintaining an arc of

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[1] Numbers in brackets refer to bibliography entries.

6 degrees per 100 feet. The borehole came within 3 feet of intercepting the Pittsburgh coalbed at 1,012 feet below the surface (fig. 1). Five horizontal methane drainage boreholes were then drilled from the surface borehole, with a cumulative length of 9,544 feet (fig. 2). The Bureau of Mines has also demonstrated accuracy in the drilling of long, horizontal, methane drainage boreholes in underground coal mines. Horizontal methane drainage boreholes have been drilled at depths greater than 2,000 feet, maintaining desired vertical and horizontal borehole trajectories within a 6-foot coalbed [4,5].

DEMONSTRATION SITE

Navajo Dam is a zoned embankment structure located in northern New Mexico, 39 miles east of Farmington, New Mexico, and about 35 miles southeast of Durango, Colorado (fig. 3). One of the key structures of the Colorado River Storage Project, it regulates the flow of the San Juan River and maintains storage for the Navajo Indian Irrigation Project. It also provides a facility for fish and wildlife conservation and recreation.

Constructed from 1958 to 1963, the dam is approximately 400 feet in structural height, 3,600 feet in crest length, 30 feet in crest width, and 2,500 feet in maximum base width. The right abutment of the dam was chosen for the location of the demonstration borehole, with a planned punchout (daylighting) near the top of the spillway (fig. 4) [6].

DRILLING EQUIPMENT

A Diamant Boart core drill, a Slimdril downhole motor equipped with bent housing, and two 3½-inch o.d. polycrystalline diamond cutter bits were used to drill the borehole.

Drill description. – The main components of the Diamant Boart DBH 700 hydraulically operated diamond core drill are the drill (or feed frame) itself, the control panel, and the power unit (figs. 5,6,7). 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, powered by a 40-horsepower, 440-V, a-c electric motor.

Downhole motor description. – The Slimdril, Incorporated, 2⅞-inch o.d. downhole motor is a high-torque, positive displacement motor that hydraulically rotates the drill bit without rotating the drill string. The downhole motor converts the hydraulic horsepower, generated by the volume and pressure of the drilling fluid, into torque and rotational speed which then drives the drill bit [7].

The components of the 2⅞-inch o.d. high-torque downhole motor are identified in figure 8. When drilling fluid is pumped through the drill string and the downhole motor at rates of 30 to 70 gal/min at differential pressures of 250 to 625 lb/in^2 (gauge), the helical stainless steel rotor rotates inside the rubber molded stator. The range of downhole motor operating parameters is shown in figure 9, and the actual demonstration drilling parameters used are provided in appendix A. 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 downhole motor. The drill bit is fastened to the drive sub. Two polycrystalline diamond cutter bits, 3½-inch o.d., one each from Longyear and Slimdril, Incorporated, were equally used to drill the demonstration borehole (fig. 10). Polycrystalline diamond cutter bits are recommended for use with downhole motors because they are designed to operate at high rotating speeds for extended periods.

Both horizontal and vertical components of the borehole trajectory can be controlled during downhole motor drilling by using control devices.

Borehole trajectory control devices. – Various types of devices can be used with downhole motors to control borehole trajectory. These include bent housings, bent subs, eccentric subs, and deflection shoes. A downhole motor equipped with a 2-degree bent housing is shown in figure 11.

While drilling, continuous contact occurs between the convex side of the bent housing and the wall of the borehole; this is commonly defined as side forces. The resultant reaction of a side force exerted on the wall of the borehole is a force exerted on the bit in the opposite direction (fig. 12). The direction of the force exerted on the bit is defined as tool face direction and is the direction that the borehole trajectory will follow. Various tool face directions and their effects on borehole trajectory are shown in figure 13.

Deflection rates pertaining to known tool face settings are rated according to the borehole inclination and azimuth (bearing) at which they change while drilling. The rate of change in borehole inclination is the vertical deflection rate, and the rate of change in azimuth is defined as the horizontal deflection rate. Site-specific deflection rates must be determined to decide what tool face setting should be applied to the preceding drilling interval to maintain desired borehole trajectory and then used to periodically project or estimate bit position 16 feet ahead of a current survey depth. Vertical and horizontal deflection rates are determined by observing the change in inclination and azimuth from one borehole survey to the next. For example, by referring to appendix B, the vertical and horizontal deflection rates observed from survey depths 449 to 459 feet were 0.09 degree/foot (0.9 degree during 10-foot interval) and 0.19 degree/foot (east is positive), respectively. A tool face setting of 60 to 80 degrees right was applied using a 2-degree bent housing while drilling from 445 to 475 feet. When the survey was conducted at 459 feet, the bit depth was 475 feet. To project the inclination at the bit depth of 475 feet, the established vertical deflection rate of 0.09 degree/foot was multiplied by 16 feet and added to the surveyed inclination at 459 feet. This resulted in a projected inclination of 101.8 degrees. The azimuth at the bit depth was projected to be 343.0 degrees by muliplying the horizontal deflection rate of 0.19 degree/foot by 16 feet and adding the 340.0-degree azimuth surveyed at 459 feet. The projected inclination and azimuth at 475 feet were close to the actual results surveyed later at 479 feet (see appendix B). Angle averaging, which is a surveying calculation method, was used to calculate projected coordinates and elevation at the bit [4,8]. Established deflection rates pertaining to tool face settings and bent housing will be 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 degrees 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 maintain the desired horizontal and vertical borehole trajectories.

SURVEYING EQUIPMENT AND PROCEDURES

Survey instrument. – The NL Sperry-Sun type B, 120-degree magnetic directional survey instrument was used during drilling to monitor borehole inclination, bearing, and tool face direction (fig. 14). The essential elements of the survey instrument are the compass/inclination unit, batteries and film loading mechanisms, lens and lamp holder, and a 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 [9].

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 into a protective casing which is inserted into a hollow drill rod and pumped through the drill rods with water to the back end of the downhole motor where it aligns with the orienting sub after impact. 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, the film disk removed, developed, and read (fig. 15). For details on conducting a survey, reading a developed film disk, and alignment of survey hardware with the bent housing, refer to [4] in the bibliography or contact NL Sperry-Sun.

Surveying accuracy. – Directional drilling accuracy is primarily dependent on borehole surveying accuracy. Factors that influence borehole accuracy include inherent inaccuracy 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's specified tolerance in measuring bearing for a recently calibrated survey instrument compass is plus or minus 0.5 degree. The resolution in reading the photographed compass bearing on the film disk is plus or minus 0.5 degree. Consequently, a potential error of plus or minus 1 degree exists in measuring borehole bearings using this particular survey instrument. Wolff and deWardt have stated that, for a compass unit in good condition, a generally accepted systematic accuracy is plus or minus 1 degree [10].

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 plus or minus 0.5 degree. The National Geophysical Data Center located in Boulder, Colorado, or the United States Geological Survey located in Reston, Virginia, can be contacted to obtain an accurate declination correction by providing them with drill site collar coordinates and elevation. The declination correction at Navajo Dam drill site was 12 degrees east plus or minus 13 minutes. The accuracy in surveying for inclination using the NL Sperry-Sun type B, 120-degree instrument is plus or minus 0.12 degree, resulting in a 0.24-degree window of inaccuracy.

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. 16). The magnitude of this source of error is difficult to determine, although Wolff and deWardt estimate that it can be on the order of plus or minus 0.2 to 0.5 degree [10].

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 NMDC (nonmagnetic drill collar). The NMDC used to drill the demonstration borehole consisted of a nonmagnetic downhole motor (nonmagnetic rotor and housing 12 feet in length, bearing package and bit made of magnetic material, 2 feet in length), and 100 feet of NQ-size wireline nonmagnetic stainless steel drill rod. Previous Bureau of Mines' experience in directional drilling of long horizontal boreholes in coal has shown that compass spacing of 20 feet from the bottom of 100 feet of NMDC sufficiently reduces drill string interference. Compass spacing inside an NMDC is estimated using the NL Sperry-Sun 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 [11]. Based on the selection chart shown for the Navajo Dam location (fig. 17), for an uncorrected bearing of N. 12° W. and inclination of 90 degrees, the compass should be located 15 feet from the bottom of a 30-foot NMDC. While drilling the demonstration borehole, the NL Sperry-Sun single-shot instrument was placed 13 feet from the bottom of the NMDC.

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 the calculation technique applied, short survey intervals will result in increased accuracy [12]. Borehole surveys were conducted at 10-foot drilling intervals at Navajo Dam. Upon completion of a survey, the inclination, bearing, and survey station depth (borehole depth minus 16 feet) were entered into the Radius of Curvature Computer Program adapted for the Hewlett Packard 15C calculator (appendix C).

Angle averaging was used periodically to check the radius of curvature results. 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 [8,12].

PLANNING THE DEMONSTRATION BOREHOLE

The borehole collar coordinates at elevation 5933.53 were established at N. 19,567.60, E. 52,697.69. The punchout was targeted to occur within a 5-foot radius of coordinates N. 20,447.31, E. 52,709.41 at elevation 6049.03 (figs. 18,19).

The right abutment bedrock consists predominantly of coarse- to medium-grained sandstone with interbedded shale and siltstone (fig. 18).

The sandstone is comprised mostly of very hard angular quartz grains, is weakly to moderately cemented, and has an unconfined compressive strength of less than 6,900 lb/in^2 [6]. The rock contains both vertical and horizontal joints. Because of thin soil cover, the exact locations and extents of the joints could not be determined, so the borehole trajectory was not planned to avoid them. However, the borehole was designed to avoid the sand-filled joint shown in figure 18. The sand-filled joint's bottom elevation was estimated to be 5,950 feet or about 16.5 feet above the collar of the borehole. To prevent drilling into the joint, the first 250 feet of the demonstration borehole were to be drilled keeping borehole elevation near the collar elevation, 5933 feet. The drilling was to continue from 250 to 340 feet while increasing borehole inclination from 90.0 degrees (horizontal) to 101.0 degrees (11.0 degrees above horizontal) which would be reached at 300- to 340-foot borehole depth. Borehole inclination was then to be maintained at or near 101.0 degrees to borehole completion to intercept the target elevation. While maintaining the desired vertical trajectory of 101.0 degrees, an attempt was to be made to maintain departure within 2 feet east or west from the planned straight-line collar to punchout trajectory (fig. 19). The departure of the straight-line collar to punchout trajectory having a bearing of N. 0°-45′-00″ E. was calculated (appendix B). This information would be used continuously during drilling to monitor deviation from the desired borehole departure.

DIRECTIONAL DRILLING THE DEMONSTRATION BOREHOLE

Before the directional drilling began, a 4-inch i.d., 34-foot-long steel standpipe was grouted into a 36-foot-long, 6-inch rotary drilled borehole (fig. 20). The borehole was reamed from 3½ inches to 6 inches using a Christensen Diamin Products diamond impregnated reamer (fig. 21). A 4-inch i.d. gate valve and water measuring equipment were attached to the standpipe to facilitate borehole shut-in if necessary and to monitor water flow produced from the borehole.

The first 250 feet of the borehole were drilled maintaining elevation near the collar elevation as planned (fig. 22). Drilling continued to a depth of 495 feet without developing the necessary increase in borehole inclination. Therefore, the borehole was abandoned to sidetrack or start a "new" borehole within the initial borehole at a depth of 289 feet. After the new borehole was started, the desired vertical trajectory was maintained to borehole completion at 885 feet.

Horizontal trajectory in the first 250 feet of the borehole was maintained to within 2.5 feet of the desired horizontal trajectory (appendix B). As drilling continued from 250 to 459 feet, horizontal borehole trajectory deviated from the desired trajectory. After the new borehole was sidetracked at 289 feet, its horizontal trajectory was maintained close to the desired course to borehole completion (fig. 23).

Effectiveness in controlling borehole trajectory. – A ½-degree bent housing and pad were used to drill the initial borehole to a depth of 455 feet (fig. 24). The desired vertical and horizontal borehole trajectories were maintained to a depth of 250 feet. The vertical and horizontal deflection rates from a depth of 250 to 455 feet were inconsistent and unpredictable. The inconsistent deflection rates causing poor trajectory control resulted from a lack of sufficient side force being generated while using the ½-degree bent housing. The weak nature of the sandstone's intergranular material is believed to have negated any potential side force generated by the ½-degree bent housing. It became apparent that the necessary increase in elevation of 112 feet and horizontal deflection of 14 feet east required to intercept the target could not be accomplished using the ½-degree bent housing. Therefore, at a depth of 455 feet, the drill string and downhole motor were removed from the borehole and the ½-degree bent housing was replaced with a 1-degree bent housing and pad.

Drilling continued from a depth of 455 feet to a depth of 495 feet using the 1-degree bent housing with pad (fig. 24). Even though the vertical deflection rates were more consistent when compared to the ½-degree bent housing, the horizontal borehole trajectory continued west instead of east. At a depth of 495 feet, the borehole was calculated to be 16.8 feet west of the target departure and 96.0 feet below target elevation. As was the case with the ½-degree bent housing, the 1-degree bent housing apparently failed to generate sufficient side force to control borehole trajectory. Thus, it was decided to abandon the borehole and to sidetrack a new borehole from within the initial borehole at a depth of 289 feet.

To accommodate the sidetrack at a depth of 289 feet, enough drill rod was removed from the borehole to position the drill bit at a depth of 275 feet (appendix D). Using the downhole motor equipped with the 1-degree bent housing, the sidetrack was started at a depth of 275 feet and completed at a borehole depth of 289 feet (fig. 22).

The initial borehole was resurveyed from 89 to 289 feet at 30-foot intervals, primarily for azimuth, after replacing defective survey hardware that was believed to have caused error in measuring borehole azimuth and tool face direction (appendix B and fig. 16). Three surveys conducted at a survey depth of 479 feet in the initial borehole provided three different azimuth, inclination, and tool face direction measurements. Two components of the survey hardware were found to be defective, the centralizing rubber washers and the muleshoe which are shown as B and C of figure 16. The centralizing rubber washers which are "sandwiched" by smaller diameter copper washers for strength were not of large enough diameter. The undersized worn washers inevitably caused the survey hardware to tilt or become misaligned with respect to the drill rod and borehole. To compound matters, the muleshoe slot was not long enough, allowing the survey hardware to rotate unpredictably as the hardware fell out of the orienting sub, and causing an erroneous tool face direction to be photographed or surveyed. To correct the problem, centralizing rubber washers were made of a softer, more flexible rubber and were sufficiently oversized at $2^{9}/_{16}$-inch diameter. When surveys were repeated at the same survey depths, the survey results were consistent.

Drilling of the new borehole resumed from 289 feet to a depth of 385 feet after replacing the 1-degree bent housing with a 2-degree bent housing equipped with a slip-on shoe positioned on the downhole motor at the apex of the housing (fig. 24). Desired borehole inclination and elevation were attained at a depth of 329 feet after only 40 feet of drilling with the 2-degree housing and slip-on shoe, and were maintained thereafter. By referring to the actual borehole survey log and the desired borehole departures in table B.1 of appendix B, it can be seen that horizontal trajectory was returned to and controlled within 2 feet east or west of the desired borehole departure (fig. 23). For the first time, control on both vertical and horizontal borehole trajectories was accomplished because the tool face settings had resulted in predictable and consistent deflection rates. Drilling with the 2-degree housing and slip-on shoe generated enough side force 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. Therefore, at a depth of 385 feet, the drill rods and downhole motor were removed from the borehole. The slip-on shoe was then removed from the downhole motor.

The demonstration borehole was completed to the final borehole depth of 885 feet using the 2-degree bent housing without the slip-on shoe (fig. 24). Actual deflection rates were consistent and predictable for directional control with the 2-degree bent housing as shown in table 1.

The horizontal borehole trajectory was maintained within 2 feet east or west of the designed trajectory except for a short interval at an approximate depth of 500 feet (fig. 23). Borehole elevation increased at an average rate of 1.98 feet per 10 feet drilled, maintaining an average borehole inclination of approximately 101.0 degrees to successfully intercept the designated target elevation (fig. 22).

Borehole punchout and investigating error in azimuth. – The actual demonstration borehole punchout depth was 885 feet at elevation 6047.14, 1.61 feet below target center and 13.81 feet southwest of target center (fig. 25). The targeted punchout was to occur within a 5-foot radius with center coordinates of N. 20,447.31, E. 52,709.41 at elevation 6049.03. The calculations from the NL Sperry-Sun surveys showed the punchout to be at elevation 6047.14, 1.5 feet below the target center, and at coordinates N. 20,439.96, E. 52,710.80, 1.4 feet northeast of the target center. The elevation error between the actual and calculated punchout was 0.39 foot. The coordinate error between the actual and calculated punchout was 15.20 feet (fig. 22).

Investigation into calculating systematic compass error caused by drill string interference has indicated that a possible error of 0.30 degree was imposed on the compass. Applying the equation developed by Blythe and Callas [13] for estimating compass spacing:

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

where C = compass correction in degrees,

F = net forces affecting compass, emu,

H = horizontal component of earth's magnetic field intensity; 23,300 nanoTesla or 0.0233 emu at Navajo Dam, provided by National Geophysical Data Center,

I = borehole inclination, 95 degrees,

and E = compass reading, 350 degrees.

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

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 degree (correction of 0.30 degree west).

A final punchout easting 52,706.16 E. was calculated by applying the compass error correction to the previously surveyed borehole bearings. This departure is 4.61 feet closer to the actual punchout than computed without applying the compass correction. Caution must be used when calculating a compass correction caused by drill string interference because pole strengths cannot be measured precisely and are not constant, but the calculation in this application would have increased borehole punchout accuracy.

Drilling parameters and penetration rates. – The bit thrust applied by the Diamant Boart drill ranged from 2,300 to 7,000 pounds (appendix A, table A.1). Table 2 relates the drilling parameters to borehole depth and degree of bent housing. The thrust required increased with borehole depth. The drill bit was driven by water supplied under pressure by two triple piston pumps (fig. 26). The pumps supplied water from two 250-gallon holding tanks to the downhole motor at 60 to 70 gal/min, which rotated the bit at speeds of 700 to 850 r/min (fig. 9). Intake waterflow was measured using an ITT Barton turbine flowmeter with battery-powered recorder that provided instantaneous flow rates in gal/min and cumulative totals in gallons (fig. 27 and appendix D). At 700 to 850 r/min, the downhole motor could generate approximately 32 horsepower. Water pressure to the downhole motor was maintained between 450 and 700 lb/in^2 (gauge) (fig. 28) differential pressure, providing a bit torque between 80 and 130 ft-lbf. However, water pressure to the downhole motor varied according to the bit thrust applied, hardness of the material drilled, and elevation of the bit.

Drilling penetration rates in the sandstone ranged from 6.4 to 40 in/min (table 2 and appendix A). While drilling the first 455 feet, drill bit thrust was sometimes reduced, slowing down penetration to enhance the removal of cuttings. A maximum penetration rate of 40 in/min was reached from 455 to 495 feet by increasing the thrust. When the 2-degree bent housing was used with the slip-on shoe, binding resulted in poor penetration rates. After the slip-on shoe was removed, increased thrust levels resulted in an average penetration rate of 11.4 in/min.

Monitoring waterflow produced from the borehole. – Drill cuttings and water produced from the borehole were monitored continuously. Drilling circulation from borehole depths of 125 to 155 feet was lost after intercepting a joint or fracture. Cuttings could not be flushed adequately, subsequently causing the "bridging" of cuttings which resulted in the drill string getting temporarily stuck in the borehole. Drilling could not continue until circulation was regained. A dye test was conducted at a borehole depth of 155 feet by adding fluorescent dye to the intake water tanks and turning the pumps on for 20 minutes. Approximately 45 minutes later, dye was observed at a water seepage collection point approximately 300 feet northwest of the drill site, showing communication from the borehole. The open joint gradually filled with cuttings, and partial circulation was established as drilling continued to a depth of 325 feet. A sudden increase in water production occurred while drilling from 325 to 335 feet indicating another joint or fracture had been intercepted. At a drill depth of 365 feet, a flow of more than 70 gal/min was estimated using a 5-gallon bucket and stopwatch. Water production did not change as drilling continued to 495 feet. After completing the sidetrack at a borehole depth of 289 feet, a Nusonic, Incorporated electromagnetic coil flowmeter and a Devar, Incorporated totalizer and strip chart recorder were installed to measure water production (figs. 29, 30, and appendix E). All three units were powered by 110-V a.c. Water production was measured continuously, averaging 101 gal/min to completion of the borehole while the drill string was in the borehole (fig. 31). Shortly after the drill string had been removed from the borehole, production was measured at 285 gal/min. However, even if the borehole produced a maximum waterflow of about 400 gal/min for the 3½-inch size diameter borehole while drilling, it would not have affected the drilling operation.

Drill cuttings were logged and collected at 10-foot drilling intervals (fig. 32). The samples, which consisted mostly of coarse- to fine-grained sandstone, were given to the Bureau of Reclamation for analysis.

CONCLUSIONS

The demonstration borehole was directionally drilled to a final depth of 885 feet at punchout. The punchout elevation was only 1.61 feet from the target center; however, the borehole coordinates were 8.81 feet southwest of the target perimeter (13.81 feet from the center).

The accuracy of directionally drilled boreholes is limited to the borehole survey system being used. The NL Sperry-Sun type B, 120-degree directional survey instrument is accurate to within 1 degree of bearing and 0.12-degree of inclination. The borehole punchout surveyed relative to the actual punchout was within the indicated accuracy of the NL Sperry-Sun survey instrument. The 2-degree bent housing was the most effective in maintaining directional control of the vertical and horizontal borehole trajectories.

The survey tool must always be calibrated and the hardware checked for defective parts before and while conducting the drilling operations.

During drilling and following completion of the borehole, substantial decreases in weir discharges were noted in the right abutment of the dam. Water levels in observation wells between the borehole and the toe of the dam dropped upon completion of the demonstration. Consequently, water table drawdowns were demonstrated as a result of the 250 gal/min discharge from the test borehole collar.

The demonstrated accuracy of directionally drilled boreholes resulted in direct construction savings for Navajo Dam seepage control modifications. The original design of constructing a drainage tunnel under the right abutment with 100-foot-long drain holes drilled from within the tunnel was modified to shorten the tunnel and increase the length of the drain holes. This will result in substantial savings of construction dollars.

Additional exploration cost savings may be realized in the area of tunnel design. Directional drilling methods can be used to accurately drill along the proposed tunnel alignment. However, logging of the borehole presents problems that need to be further refined before this method of tunnel exploration can replace present exploration methods.

Table 1. – Measured deflection rates using 24 degree 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°	− .02 to − .06	− .04	NA	.13R
120° to 140°	− .07 to − .10	− .08	.01R- .13R	.07R
140° to 160°	NA	− .06	NA	.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°	NA	− .13	NA	.07L
120° to 140°	− .07 to − .20	− .12	.53L− .01R	.24L
140° to 160°	NA	− .16	NA	.11R

NA 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.

Table 2. – Drilling parameters and penetration rates

Borehole depth (ft)	Bent housing (degrees)	Average thrust force (lb)	Average bit rotation (r/min)	Average bit torque (ft·lbf)	Average penetration (in/min)
36 – 455	1/2 w/pad	4065	825	178	20.5
455 – 495	1 w/pad	4660	757	172	40.0
289 – 385	2 w/shoe	4660	802	167	6.4
385 – 885	2	6060	796	132	11.4

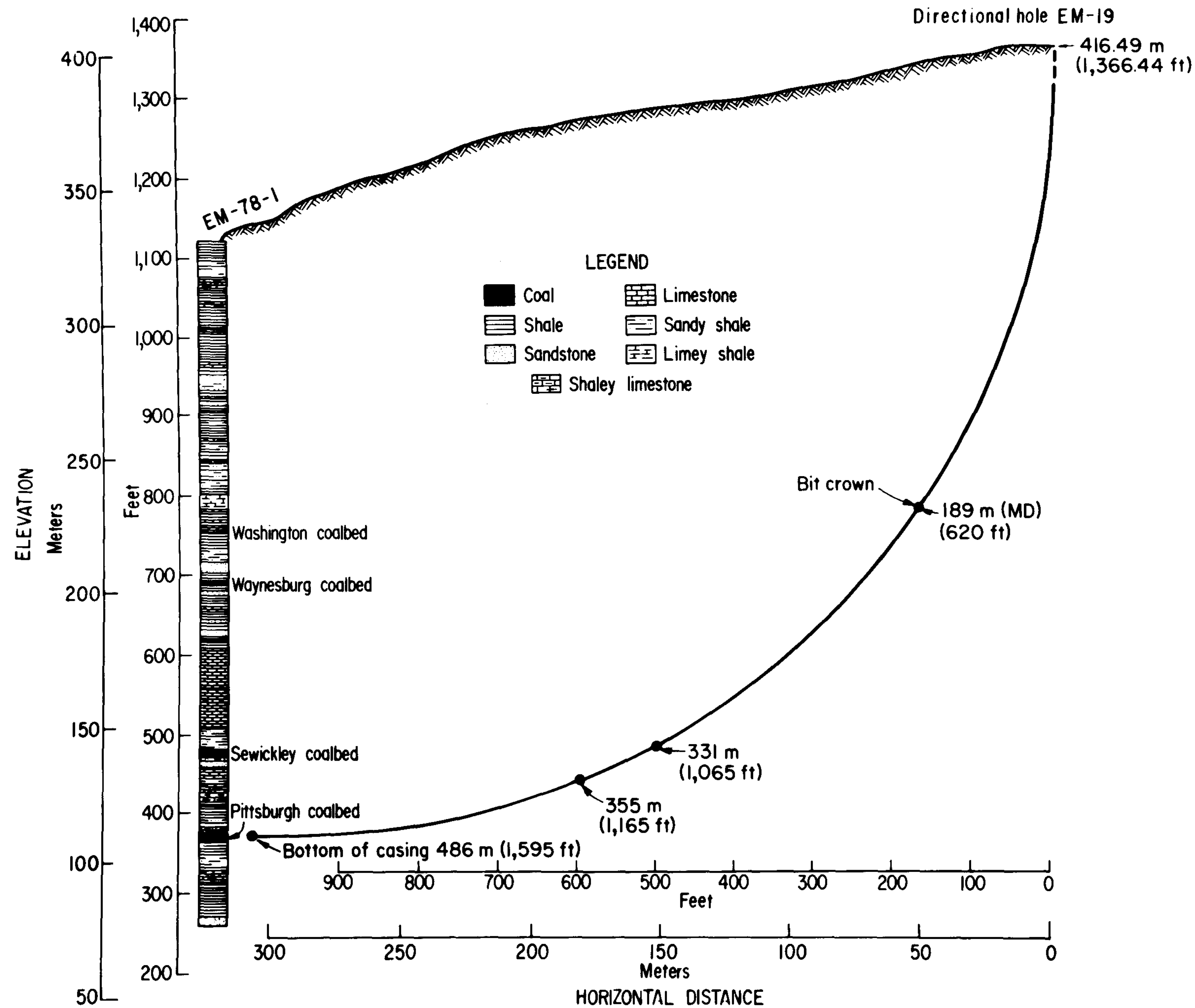


Figure 1. – Vertical section of directional surface borehole drilled to intercept the Pittsburgh coalbed.

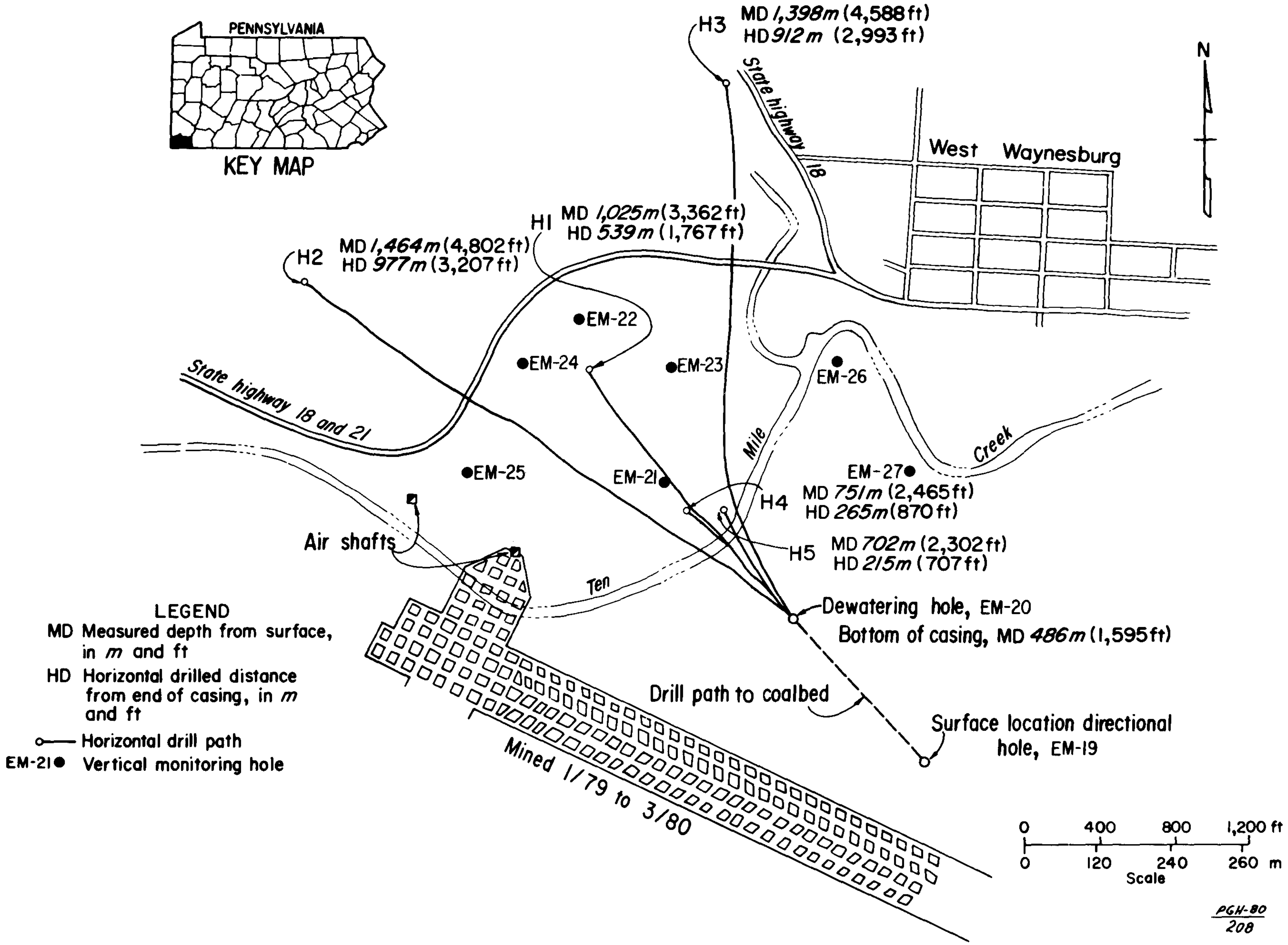


Figure 2. – Plan view of multiple directionally drilled boreholes in the Pittsburgh coal bed from a single surface borehole.

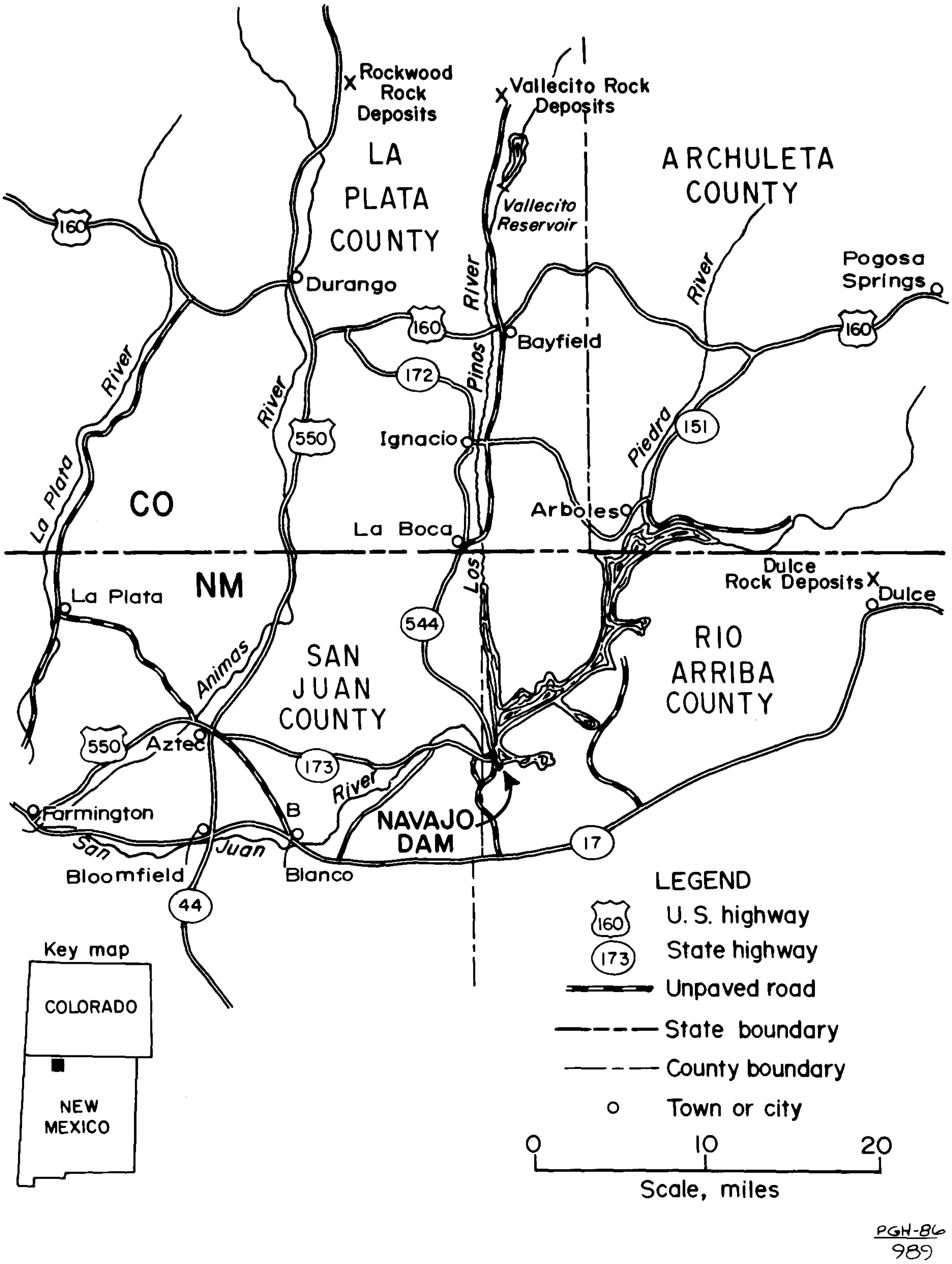


Figure 3. – Navajo Dam location map.

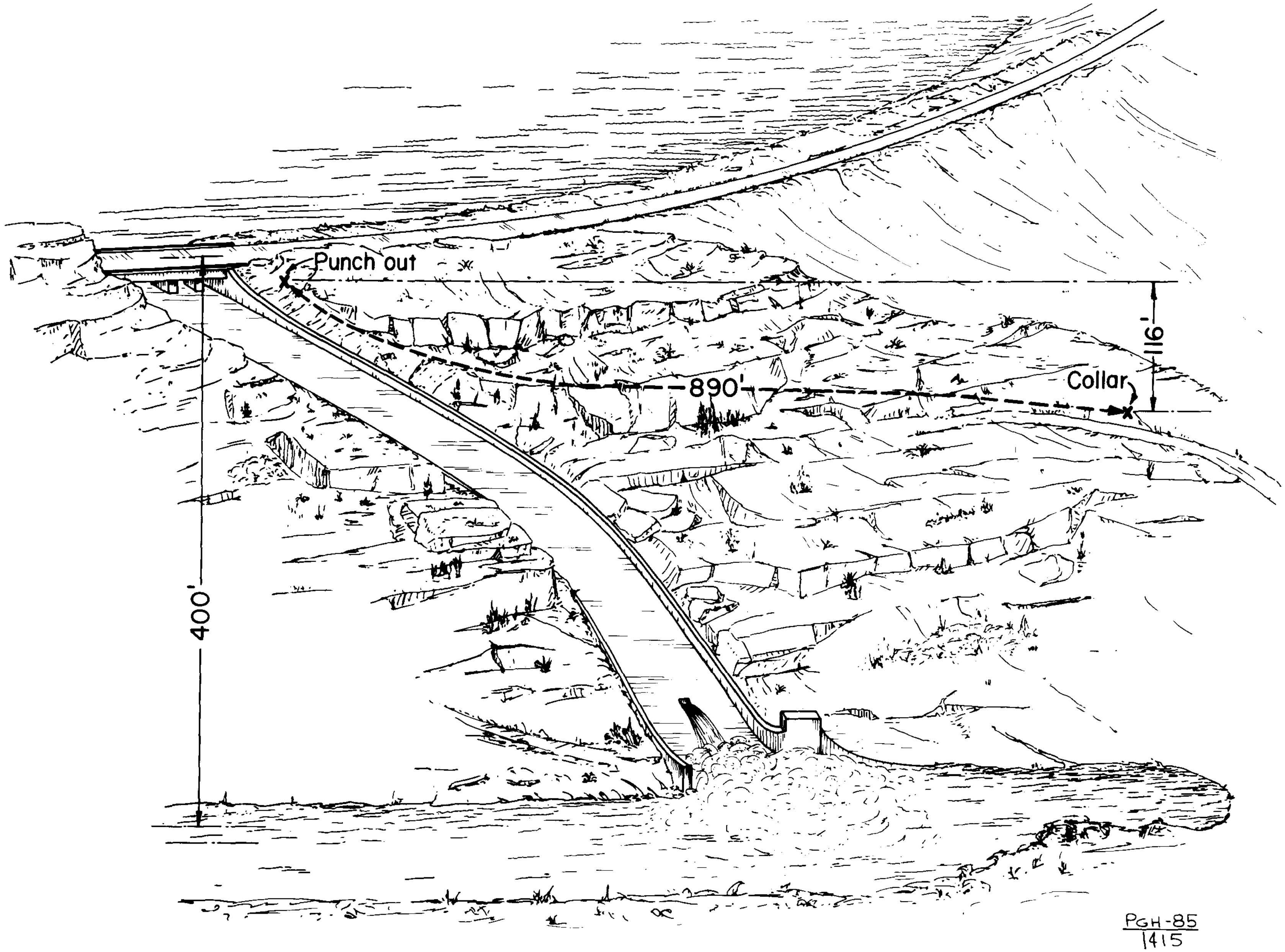


Figure 4. – Navajo Dam right abutment.

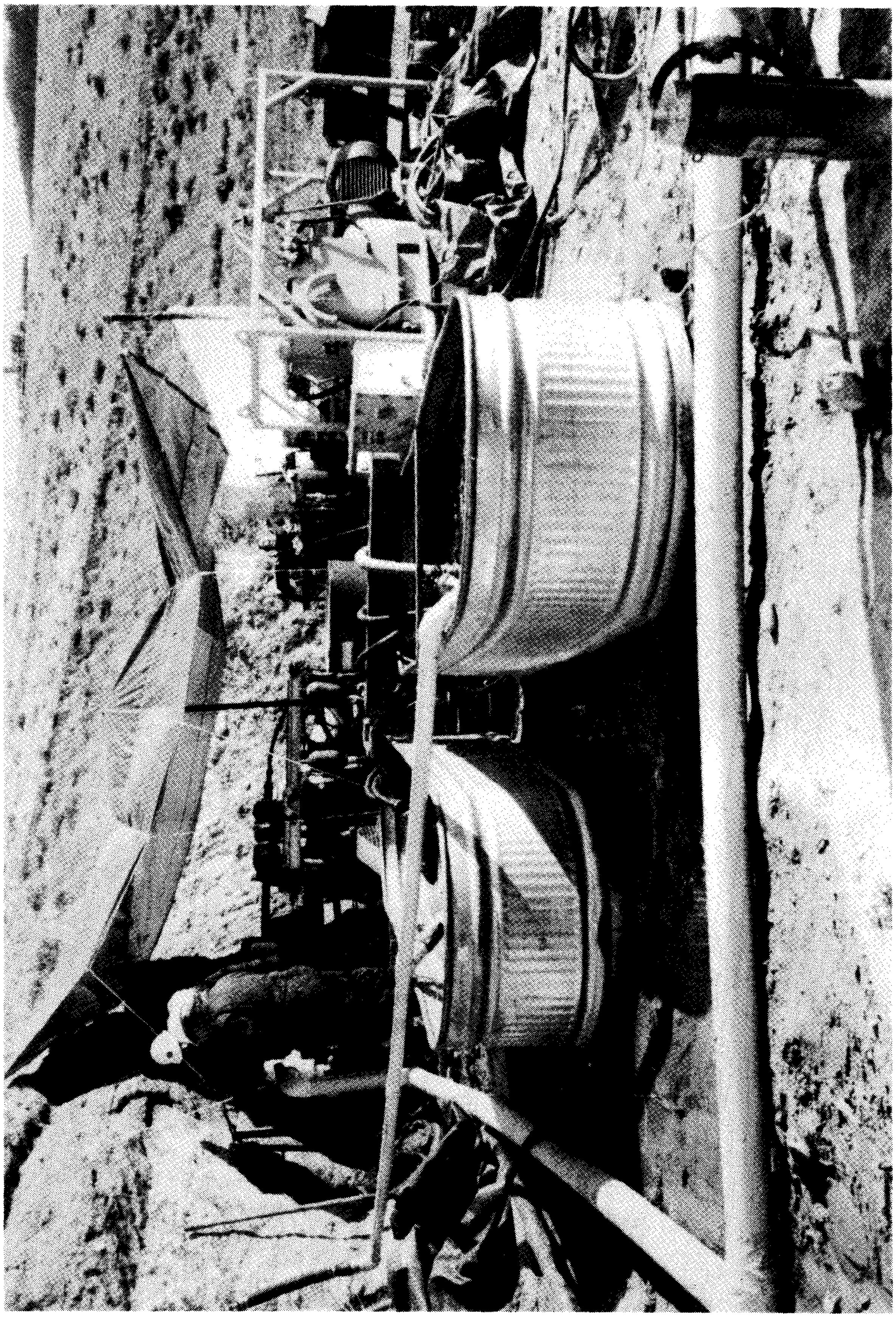


Figure 5. – Drill site.

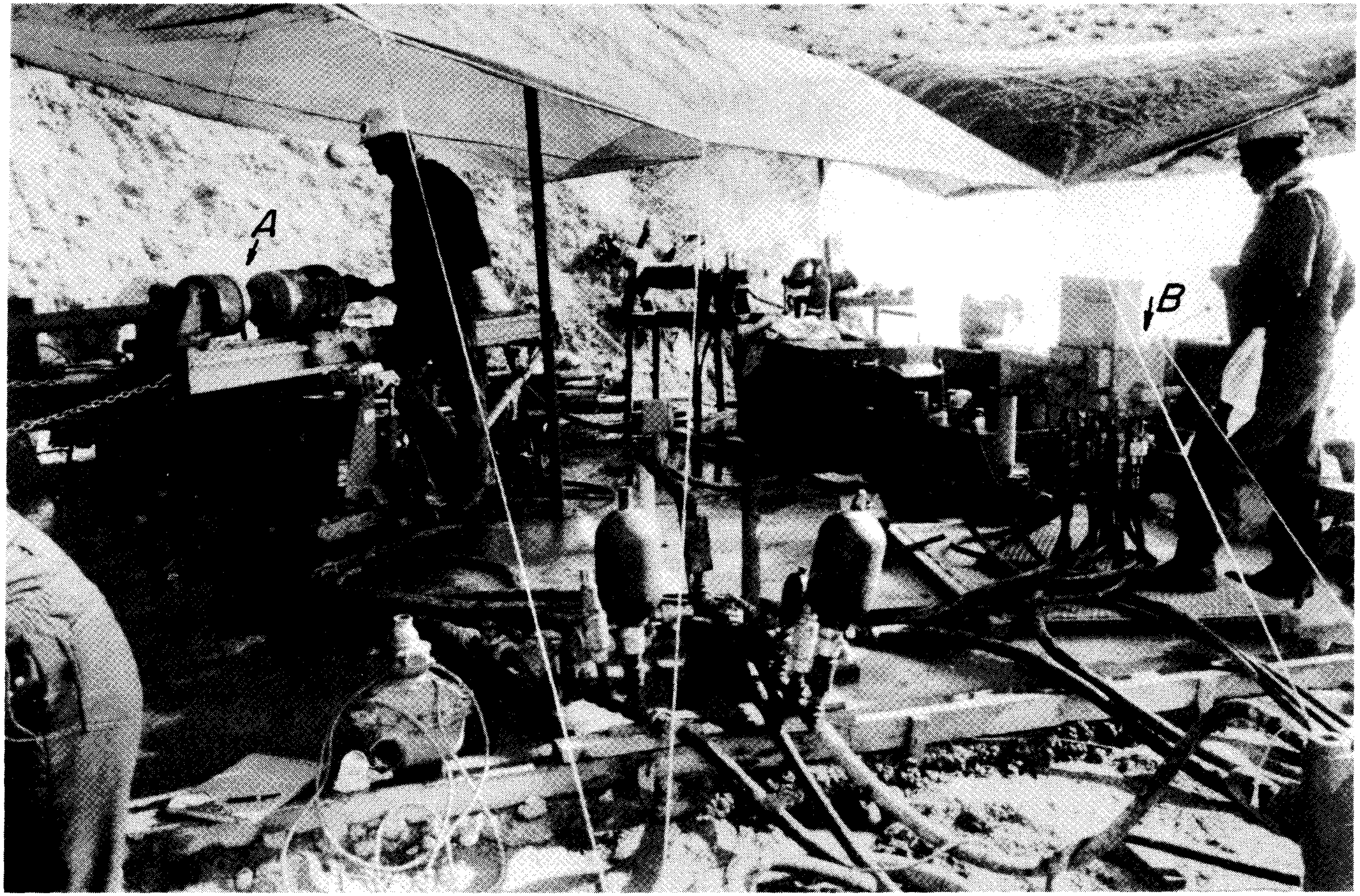


Figure 6. – Diamant Boart hydraulic drill (A) drill or feed frame, and (B) control panel.

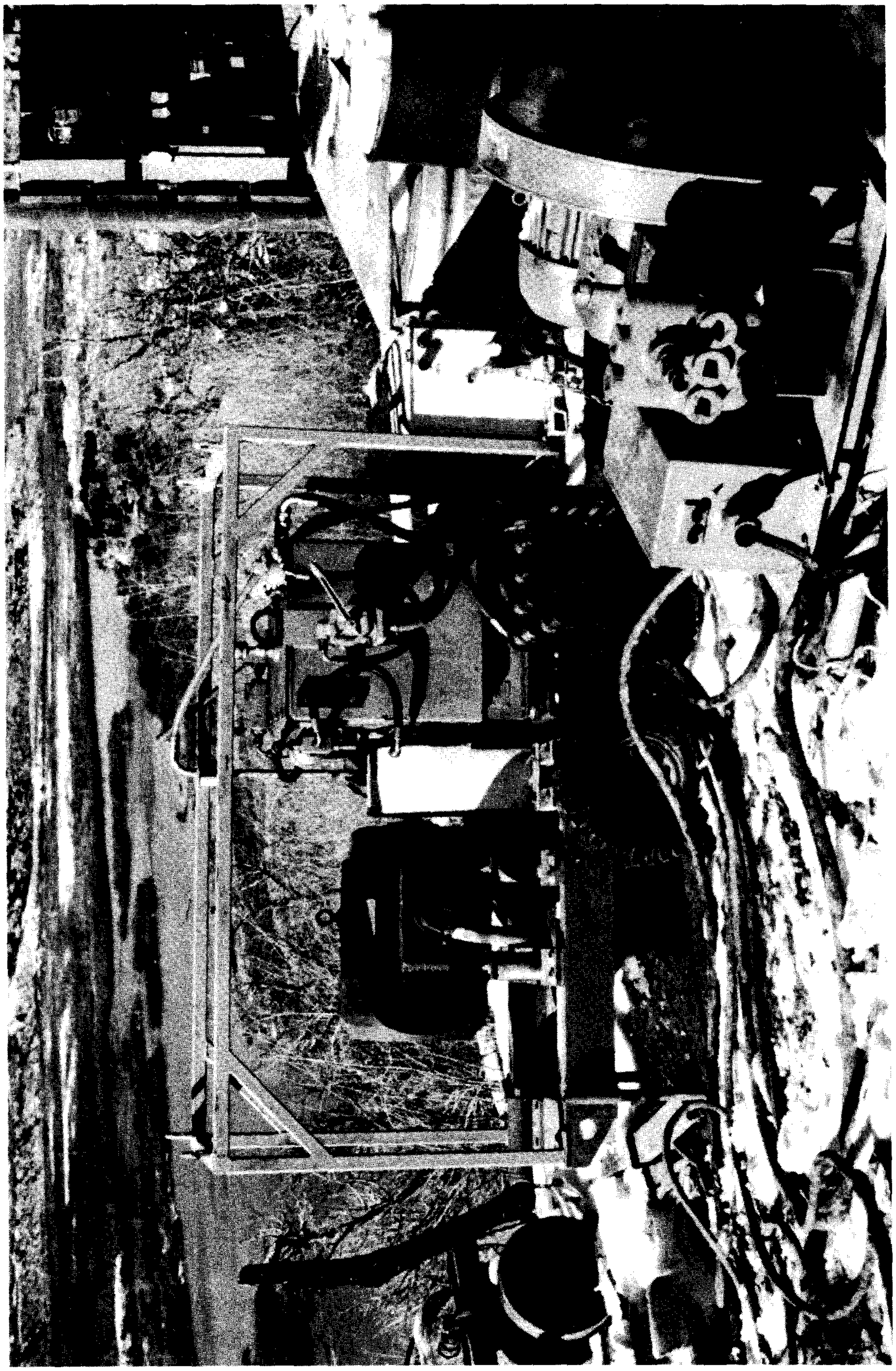


Figure 7. – Diamant Boart power unit.

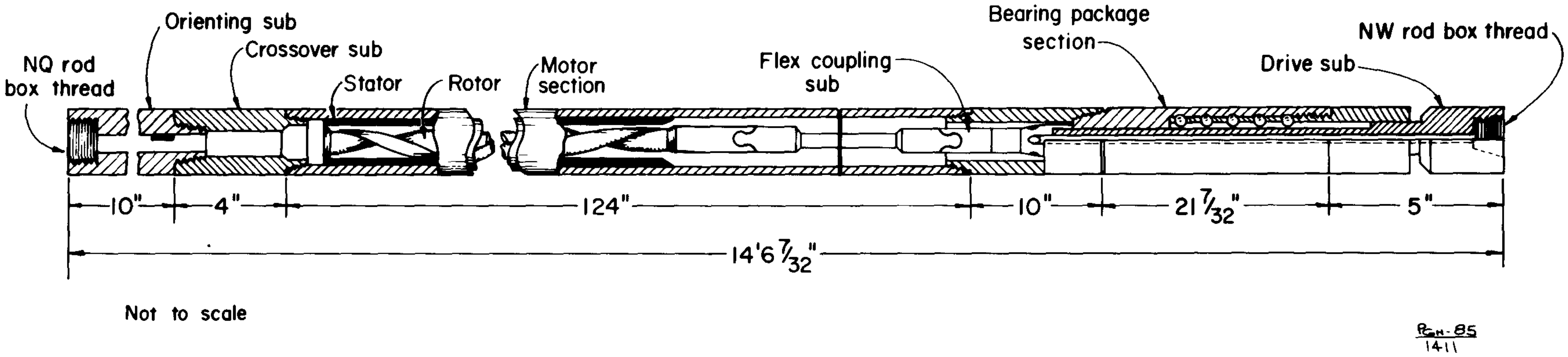


Figure 8. – Slimdril high torque downhole motor, 2⅞-in o.d.

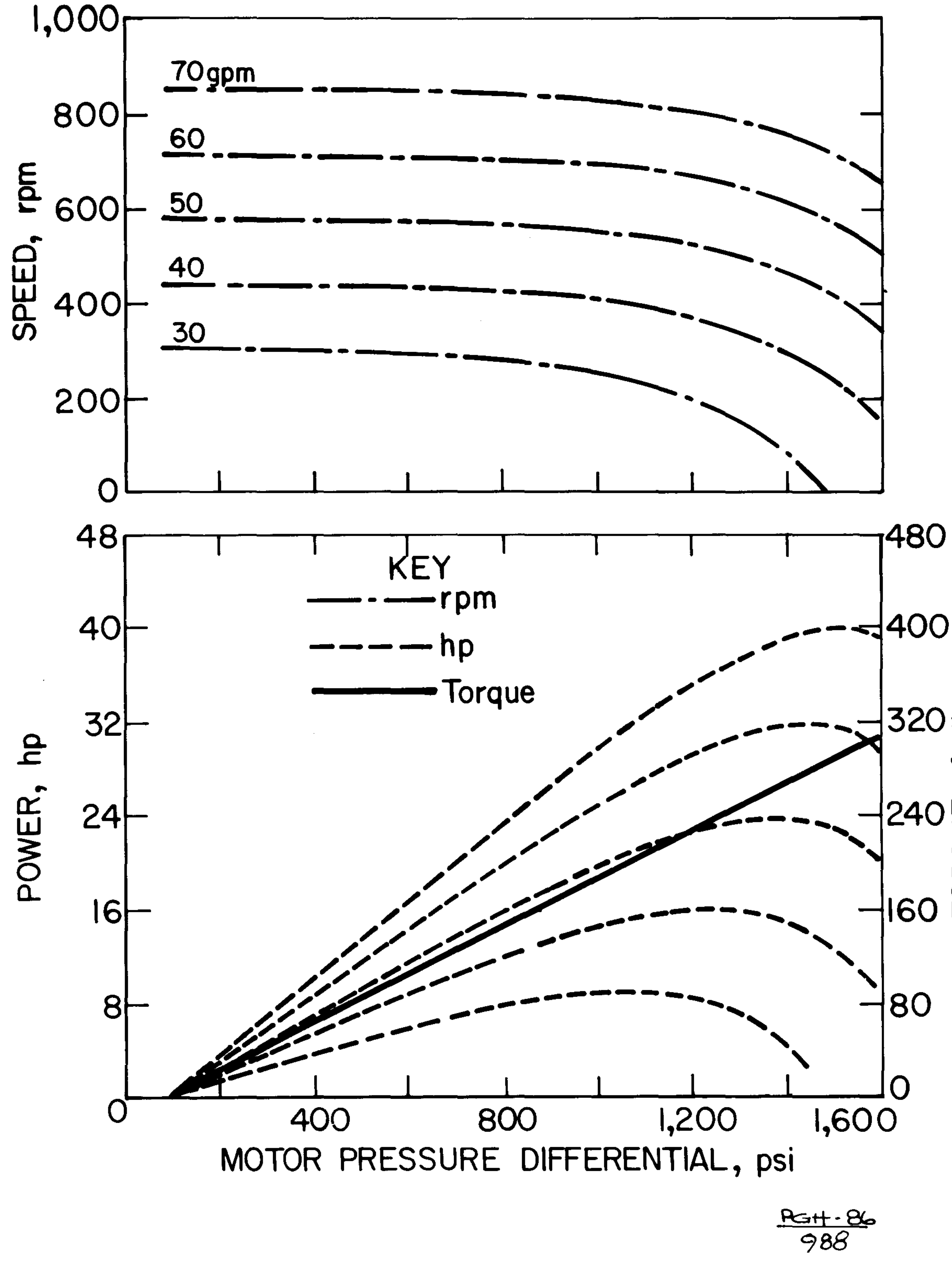


Figure 9. – Slimdrill downhole motor operating parameters.

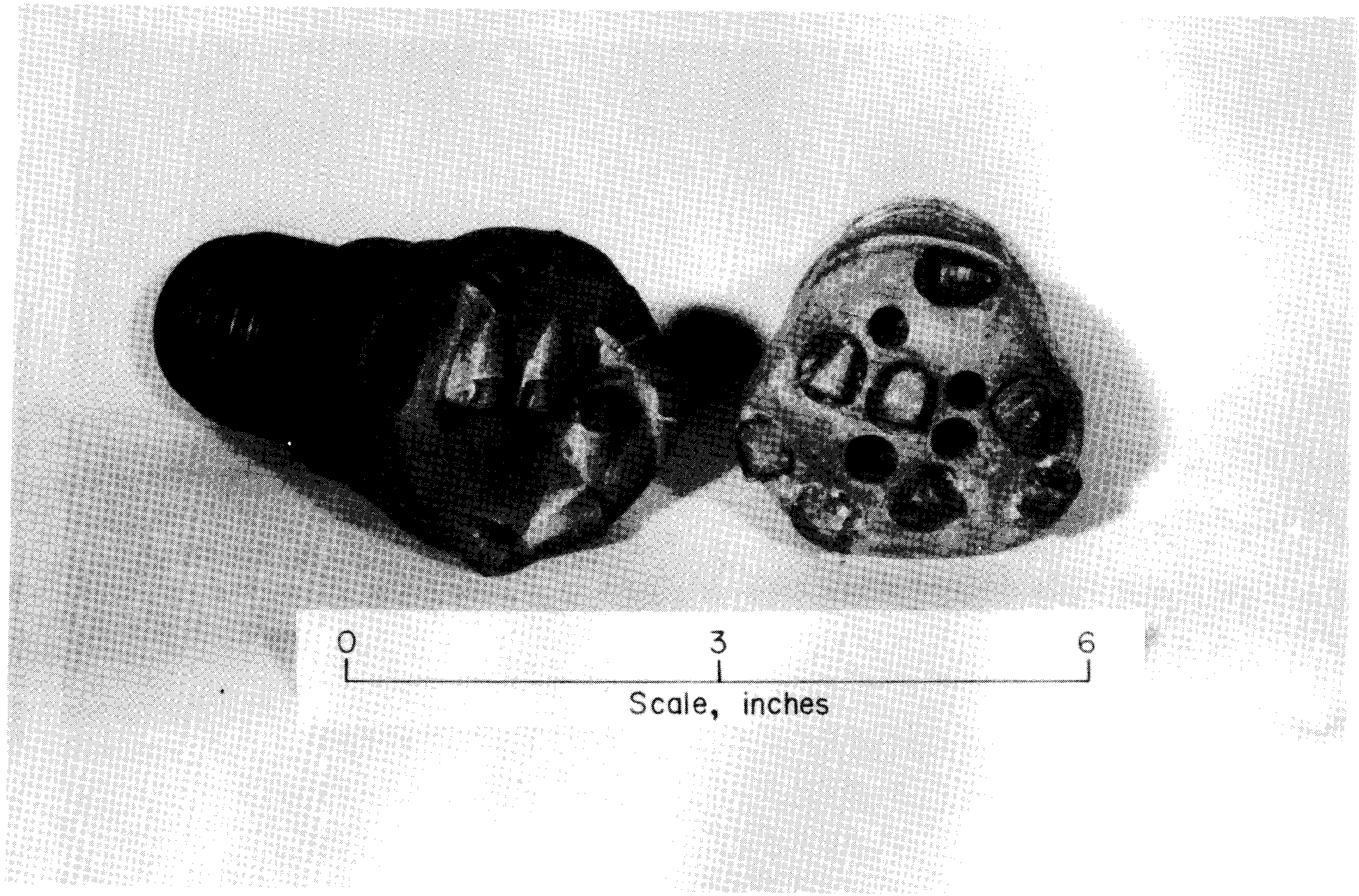


Figure 10. – Polycrystalline diamond cutter bits.

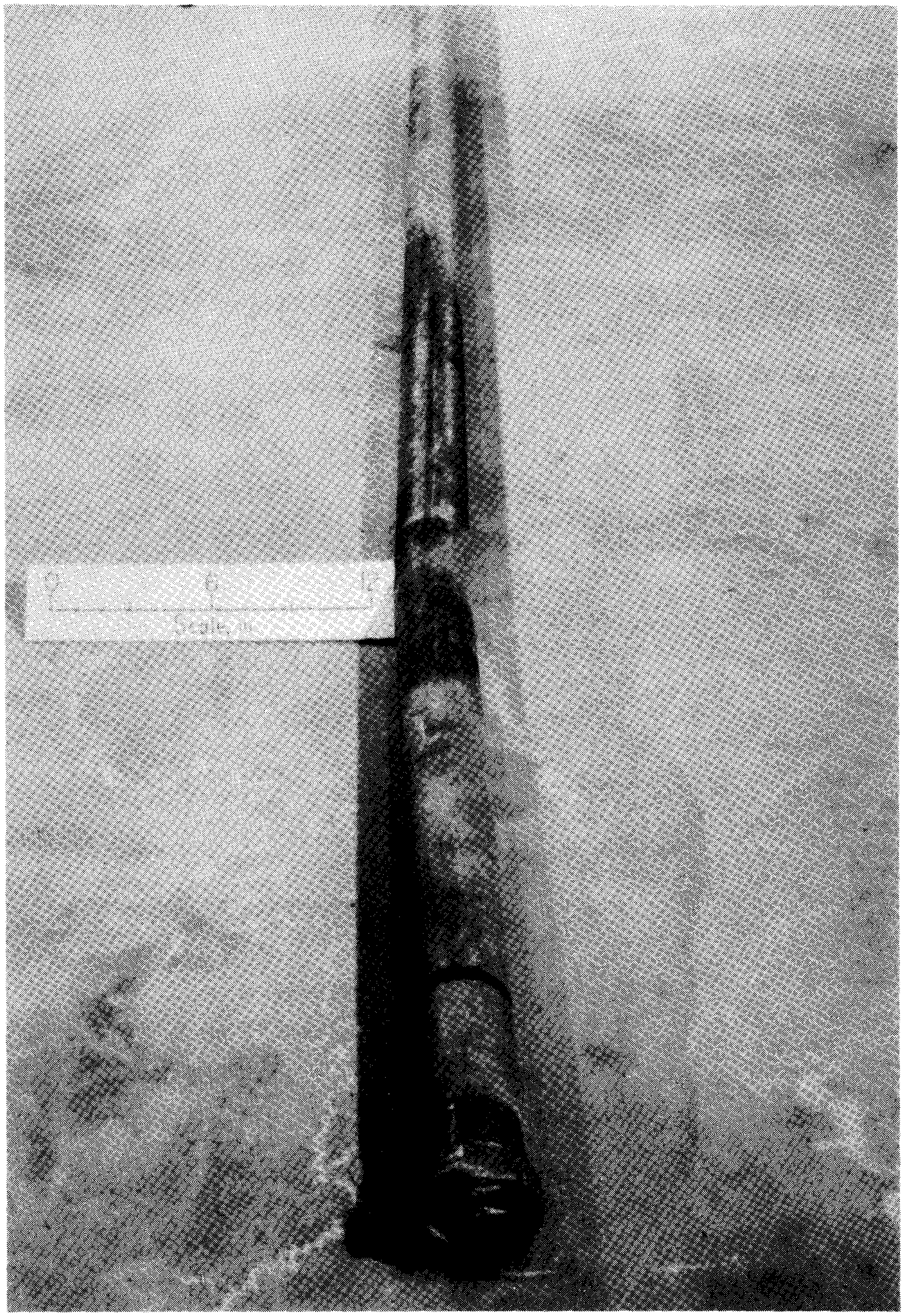
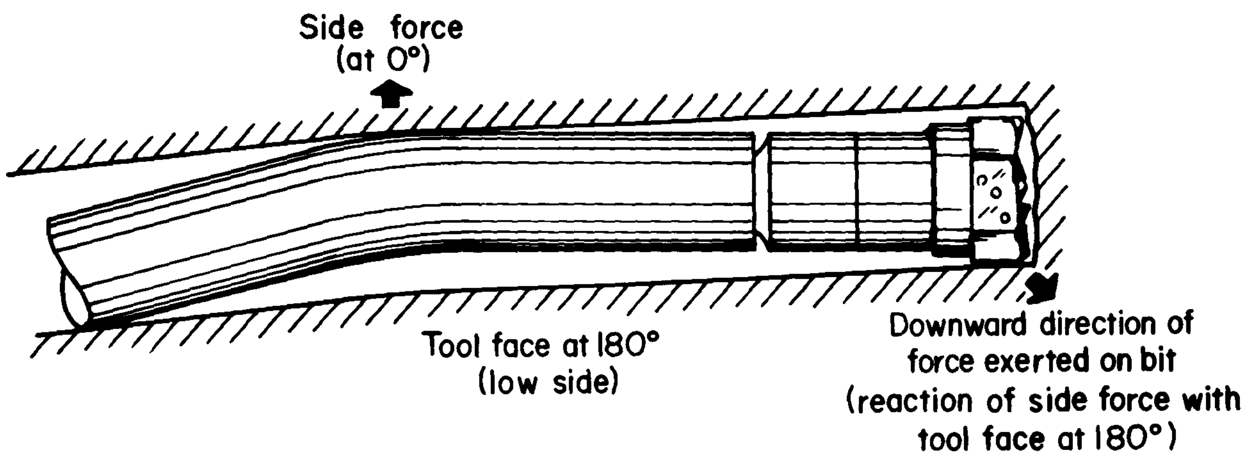


Figure 11. – Downhole motor equipped with a 2-degree bent housing.



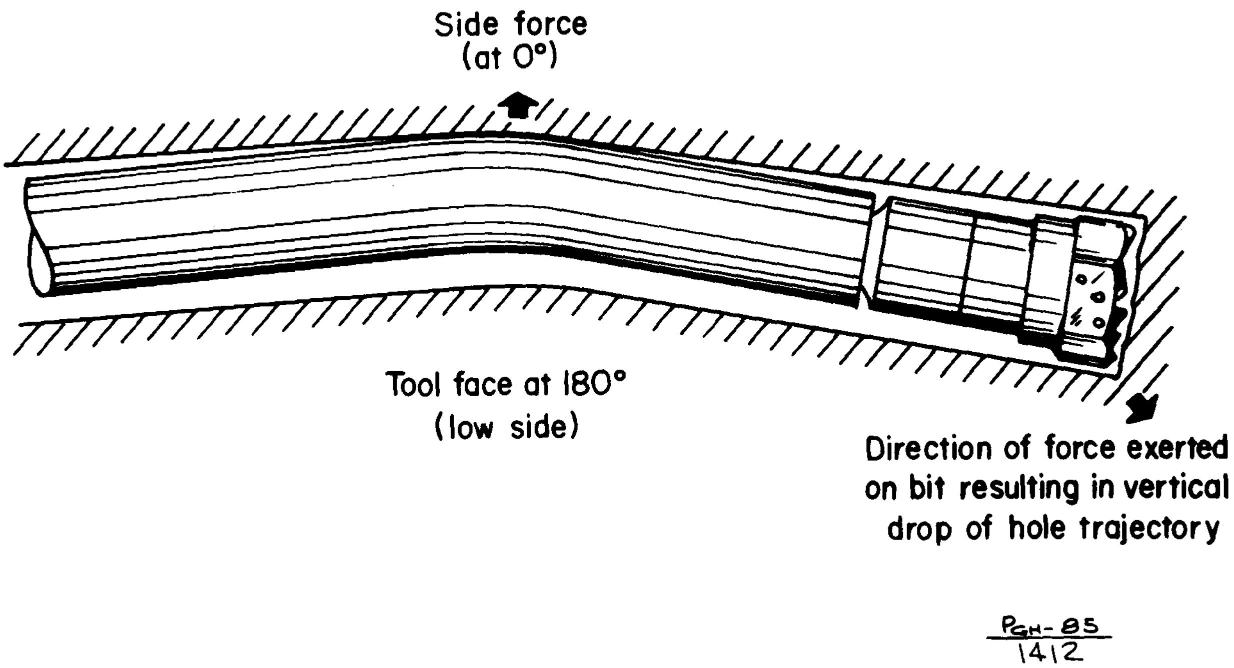


Figure 12. – Side force diagram.

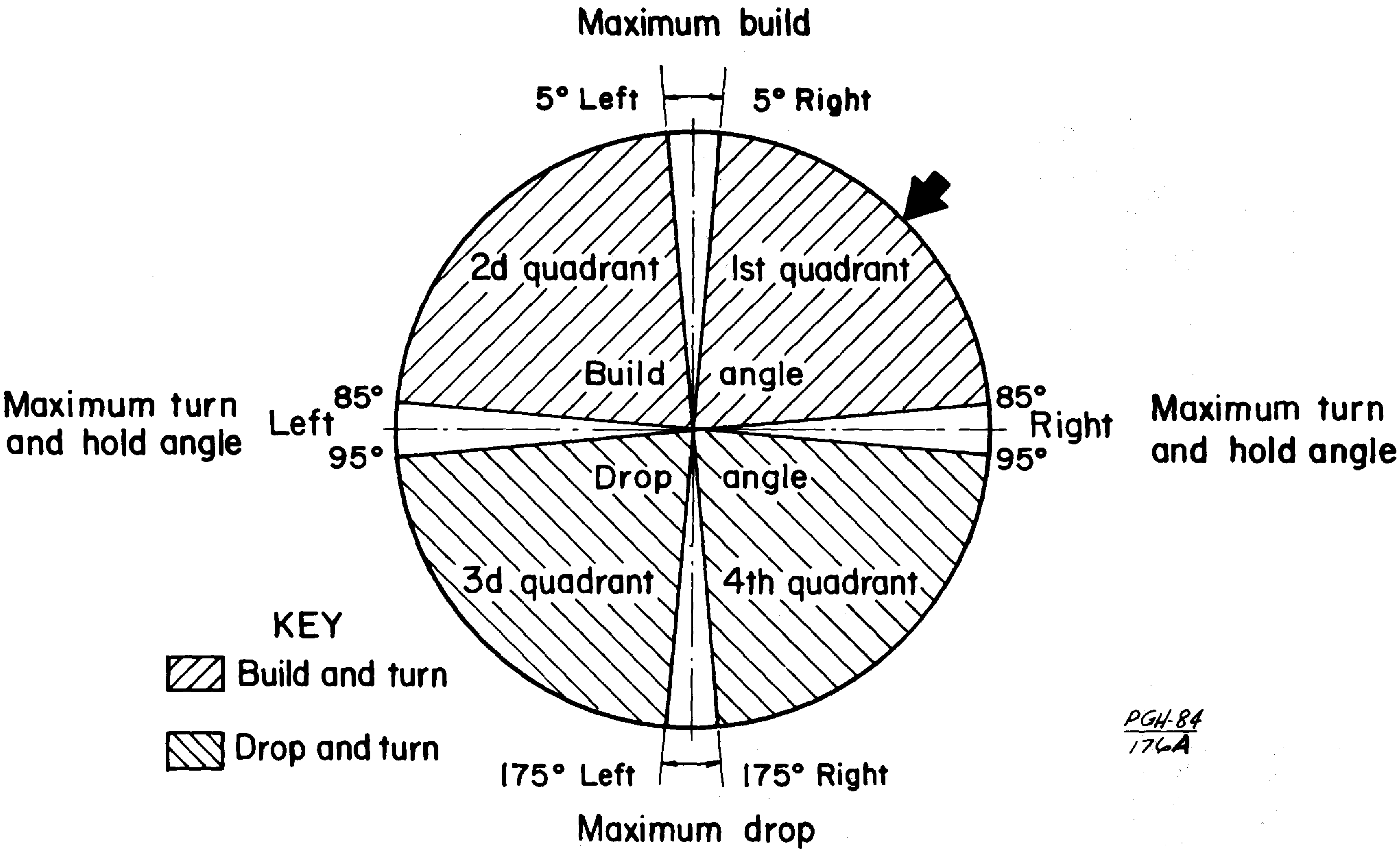


Figure 13. – Various tool face settings & their effects on borehole trajectory. Note: Black arrow depicts tool face setting of 45 degrees right, which would result in borehole trajectory building inclination and azimuth turning right (east).

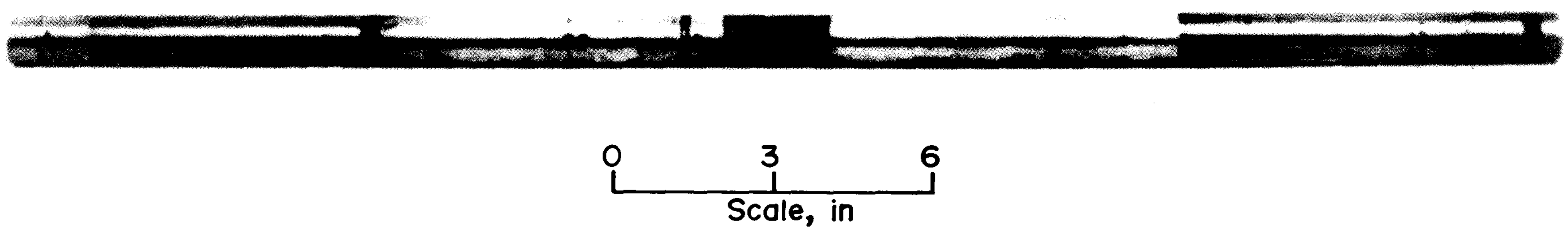


Figure 14. – Single shot directional survey instrument.

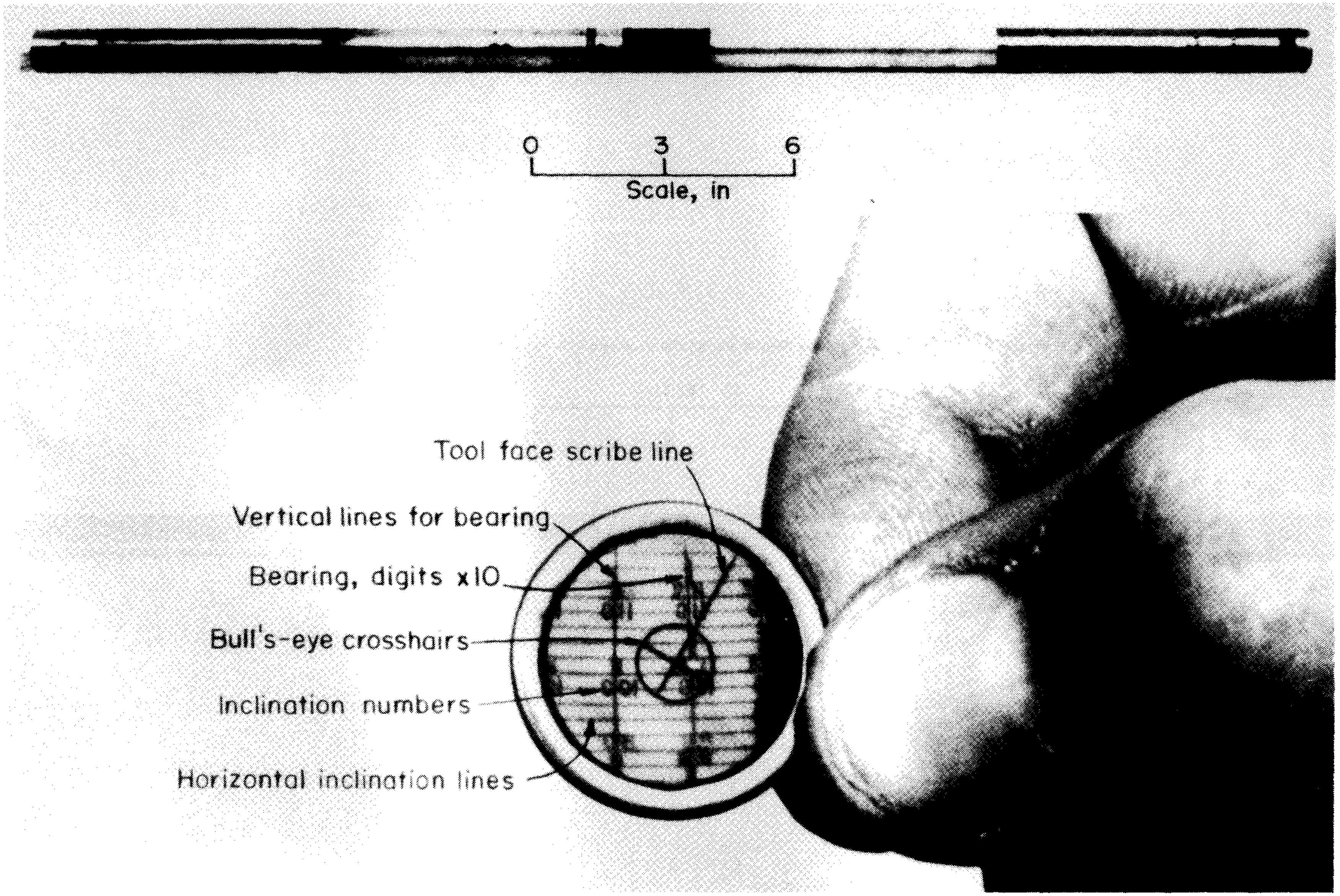


Figure 15. – Reading a developed survey film disk. Note survey results of inclination of 101.8, Bearing N8°W (uncorrected for declination), tool face of about 32° left. Tool face reader not shown. Also, note that due to photographic effects, left is right and right is left when reading tool face direction.

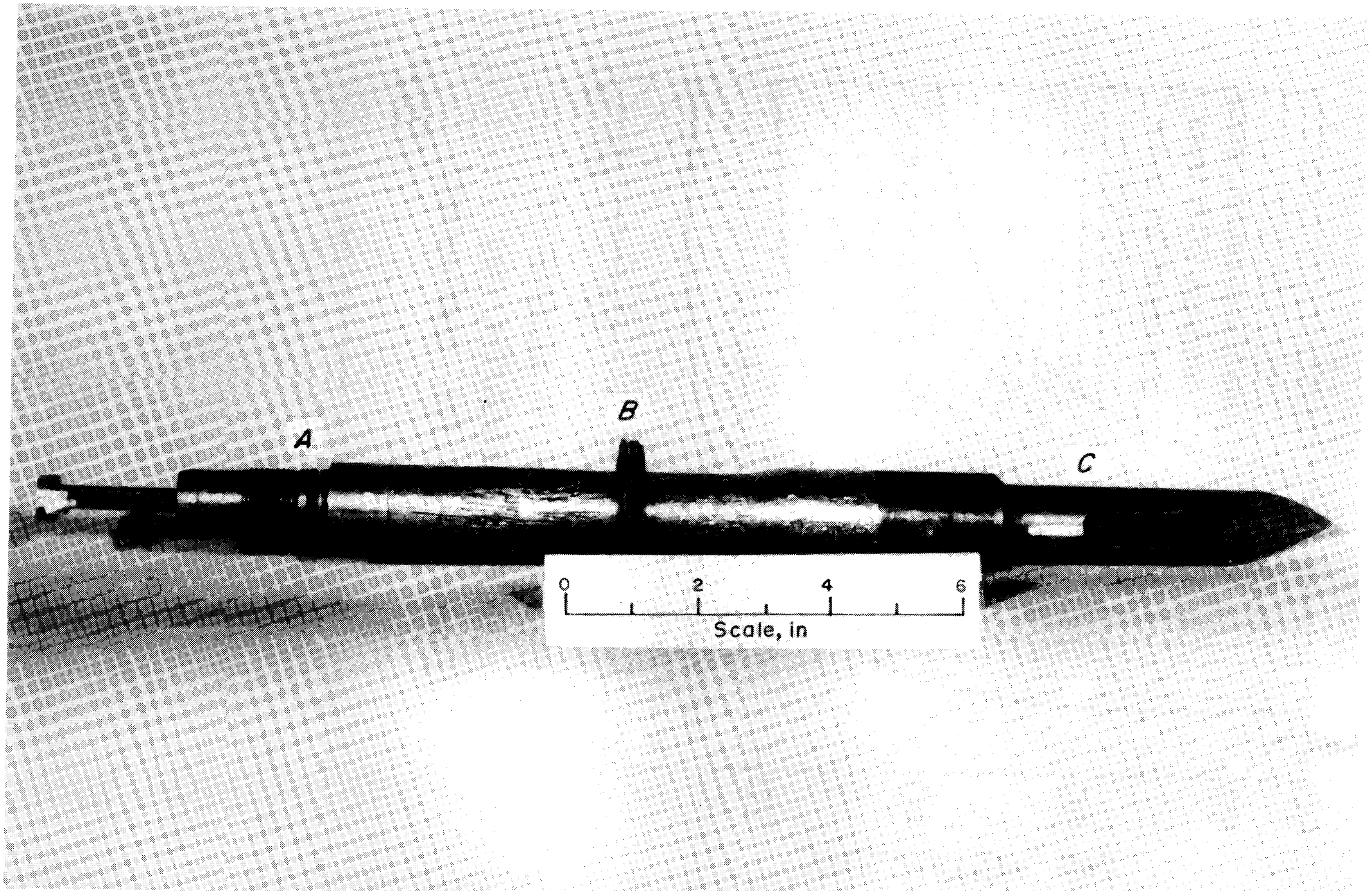


Figure 16. – Survey hardware: A, snubber; B, centralizing washers; C, muleshoe.

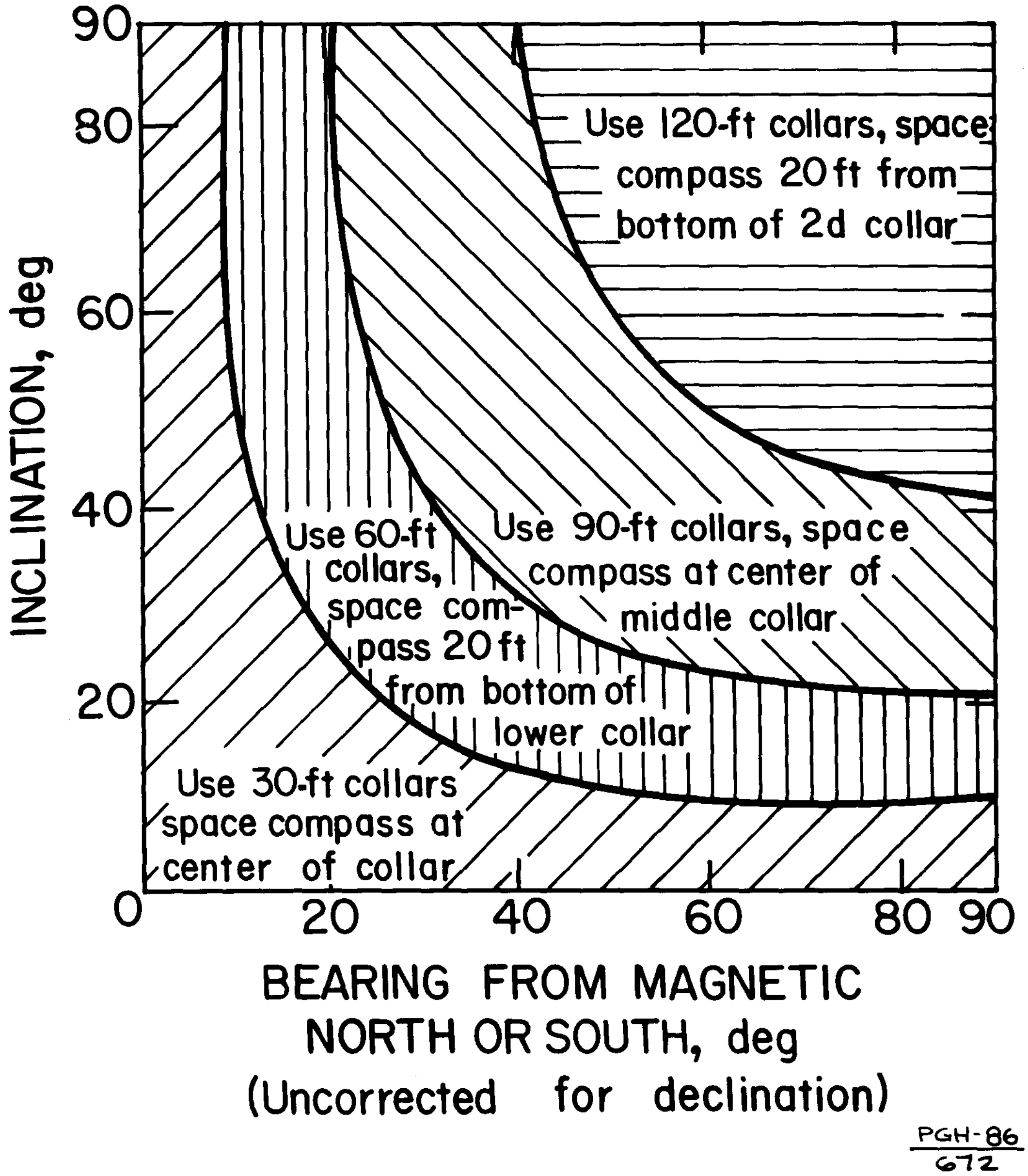


Figure 17. – Nonmagnetic drill collar and compass spacing chart.

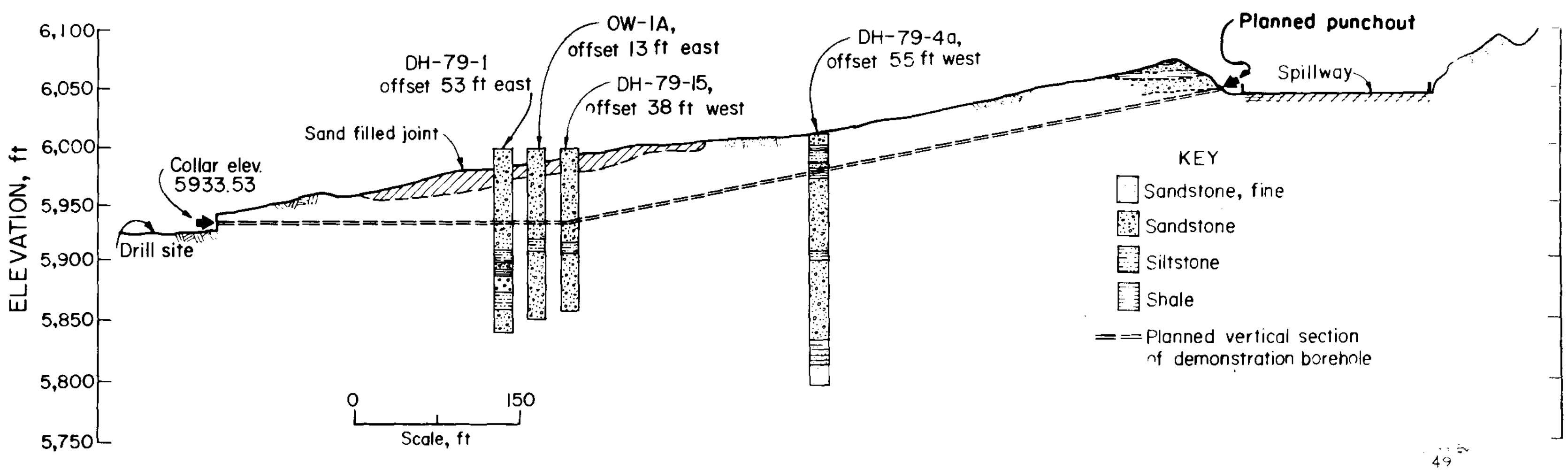


Figure 18. – Vertical section of planned demonstration borehole.

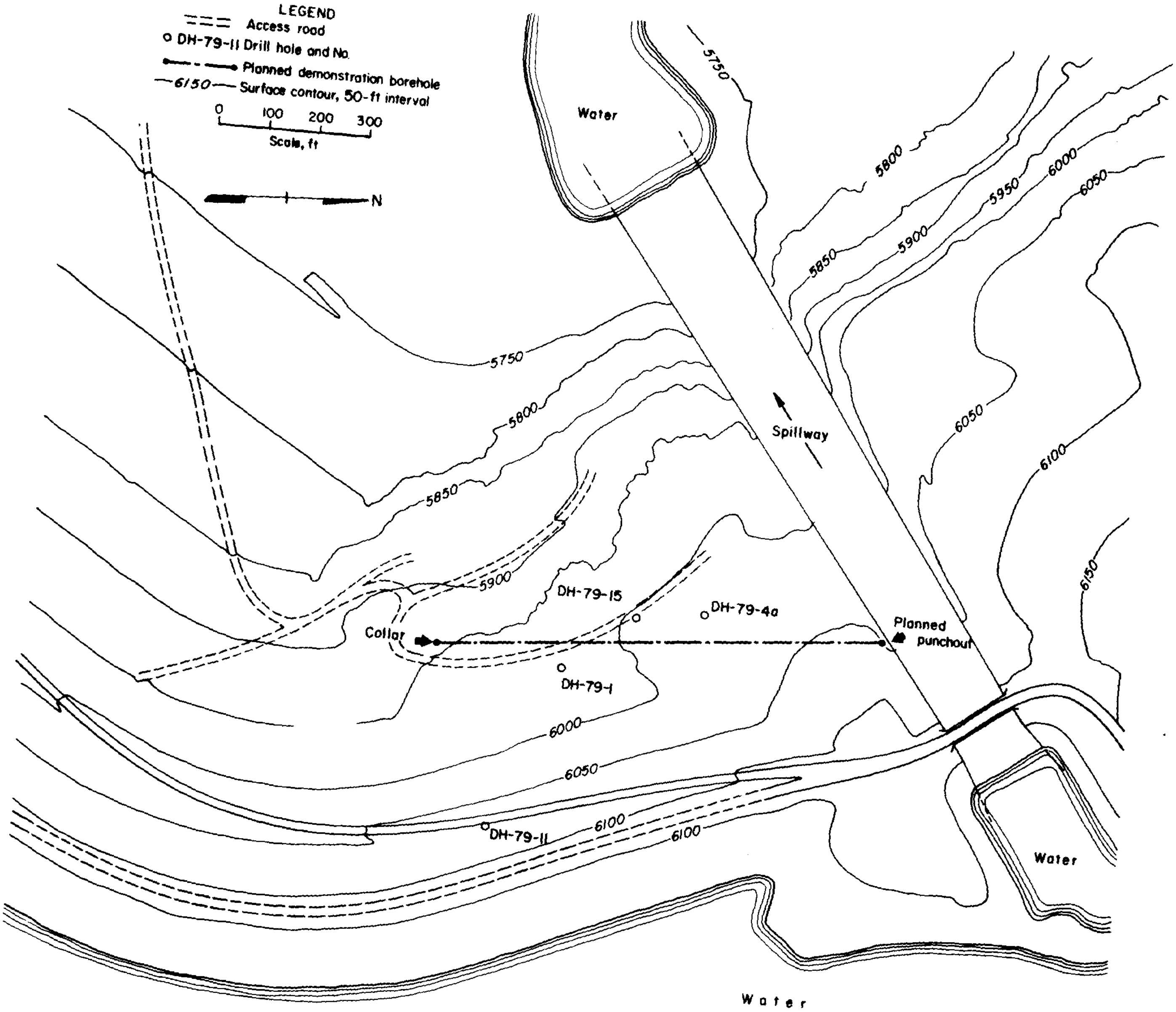


Figure 19. – Plan view of demonstration borehole.

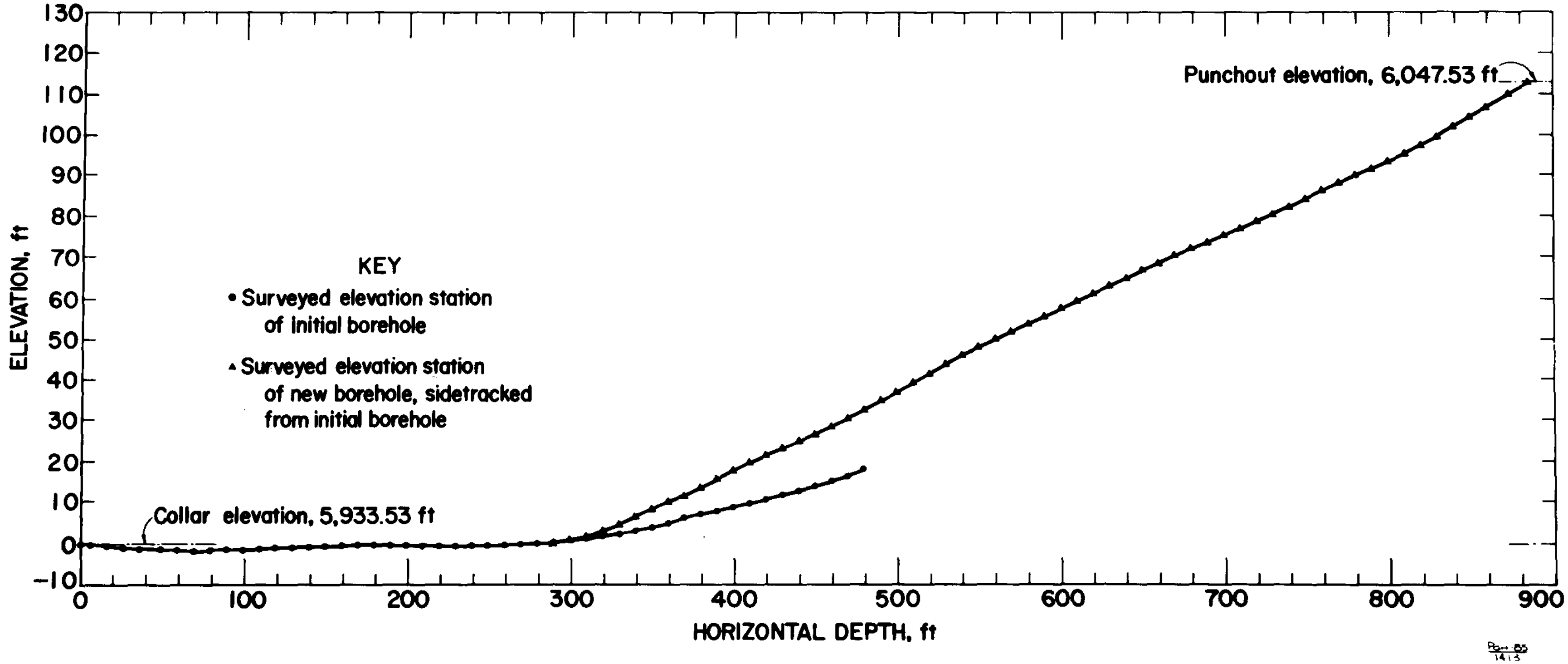


Figure 22. – Vertical section of demonstration borehole.

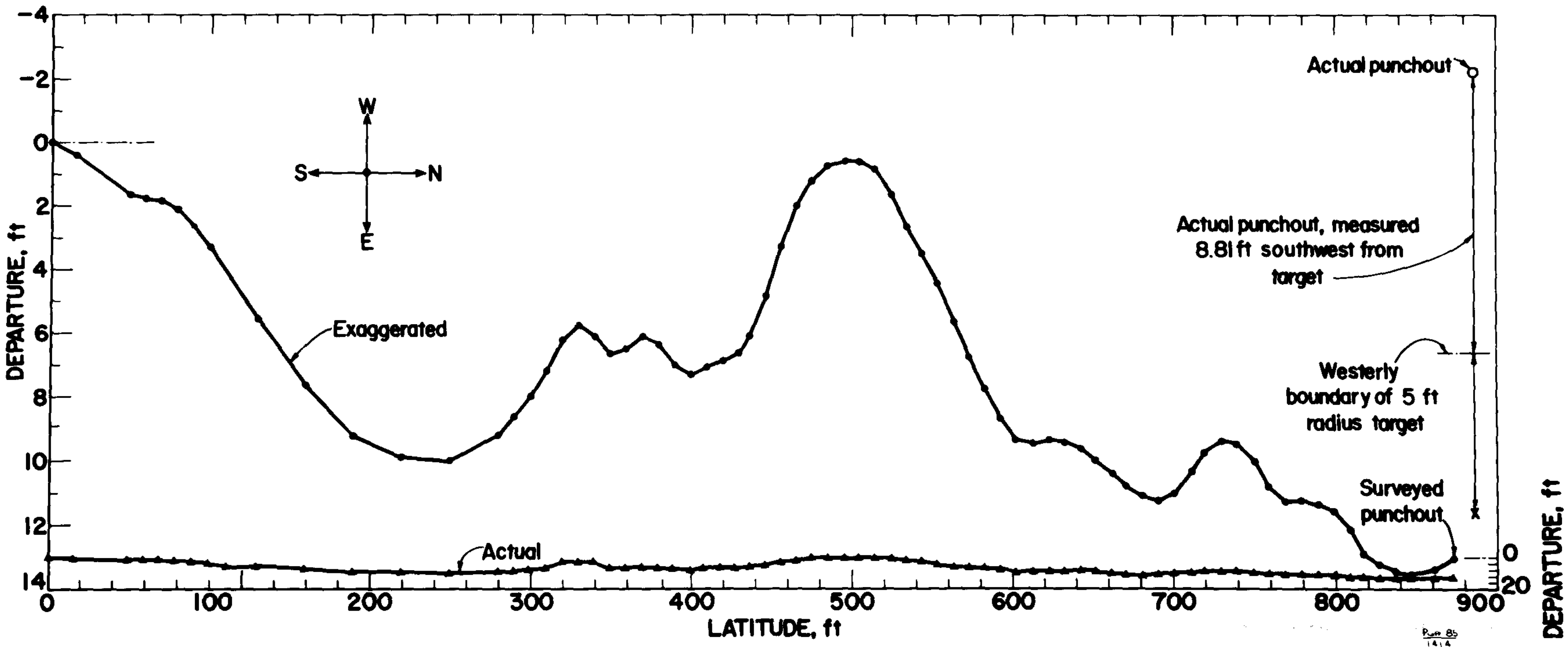


Figure 23. – Plan view of demonstration borehole.

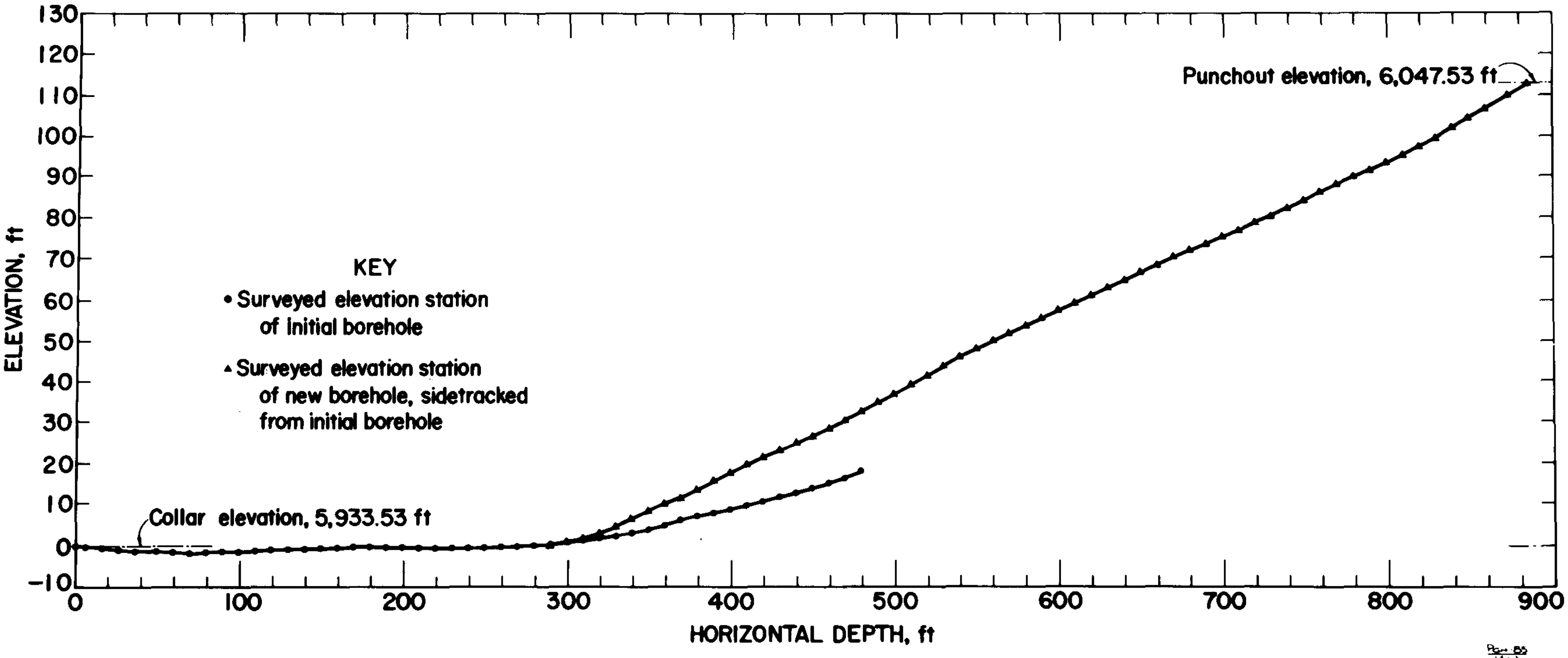


Figure 22. – Vertical section of demonstration borehole.

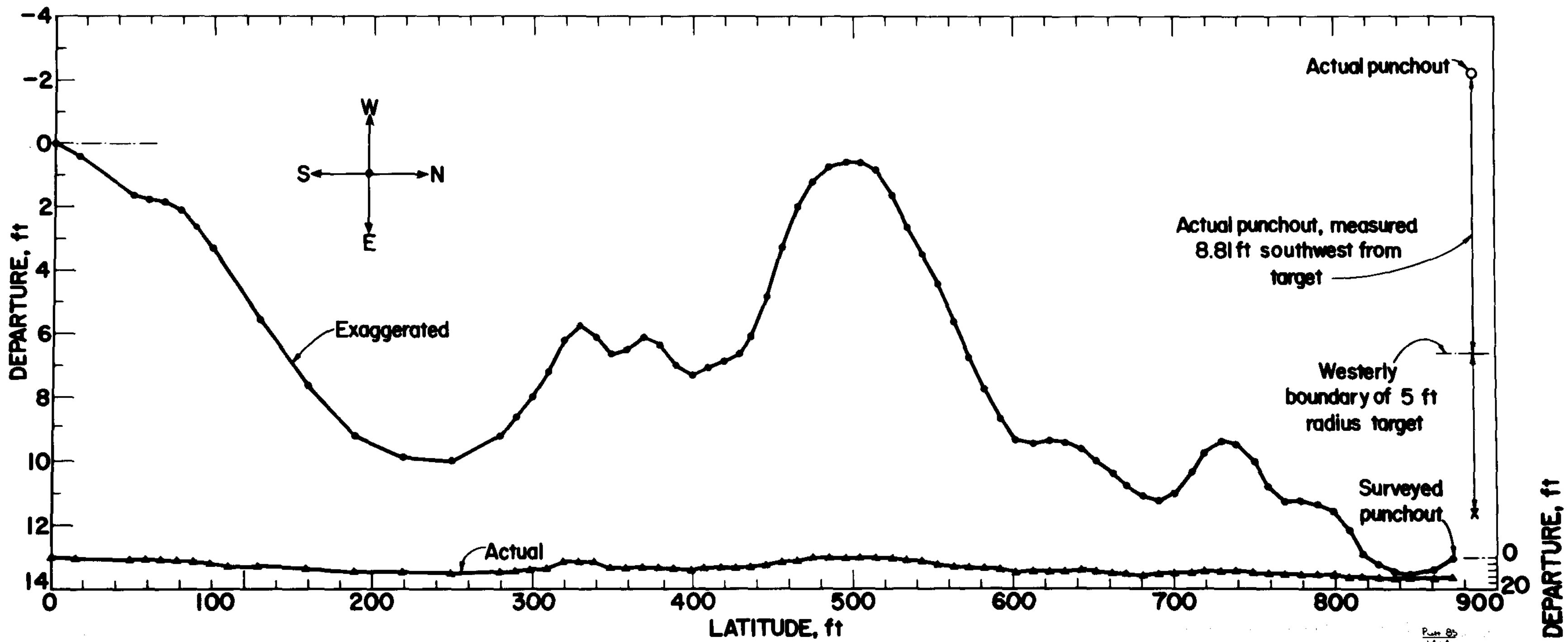


Figure 23. – Plan view of demonstration borehole.

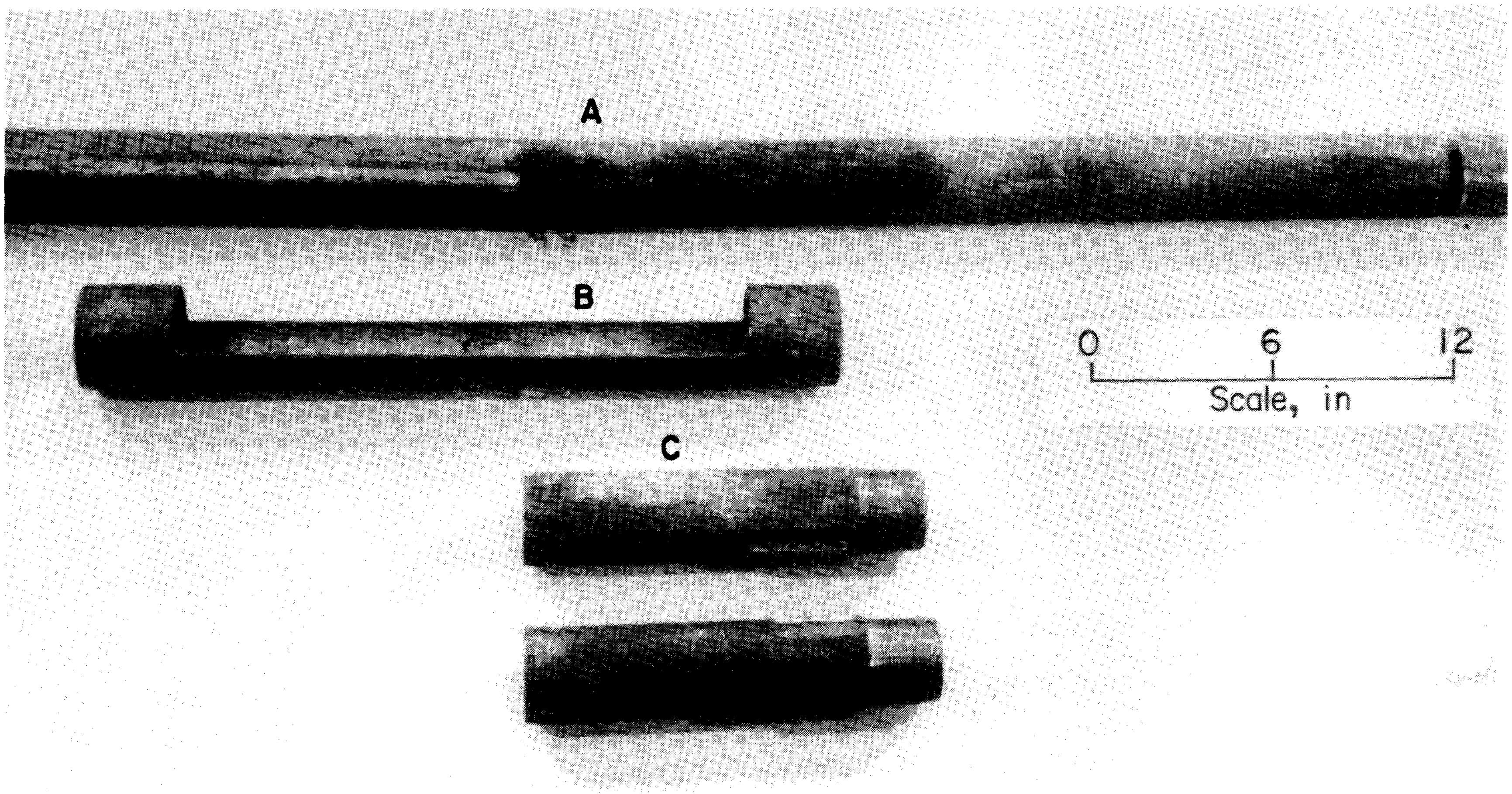


Figure 24. – Various Slimdril 2-degree bent housings on downhole motor: (A) slip-on shoe, (B) 1-degree bent housing, (C) ½-degree bent housing.

Figure 25. – Borehole punchout.

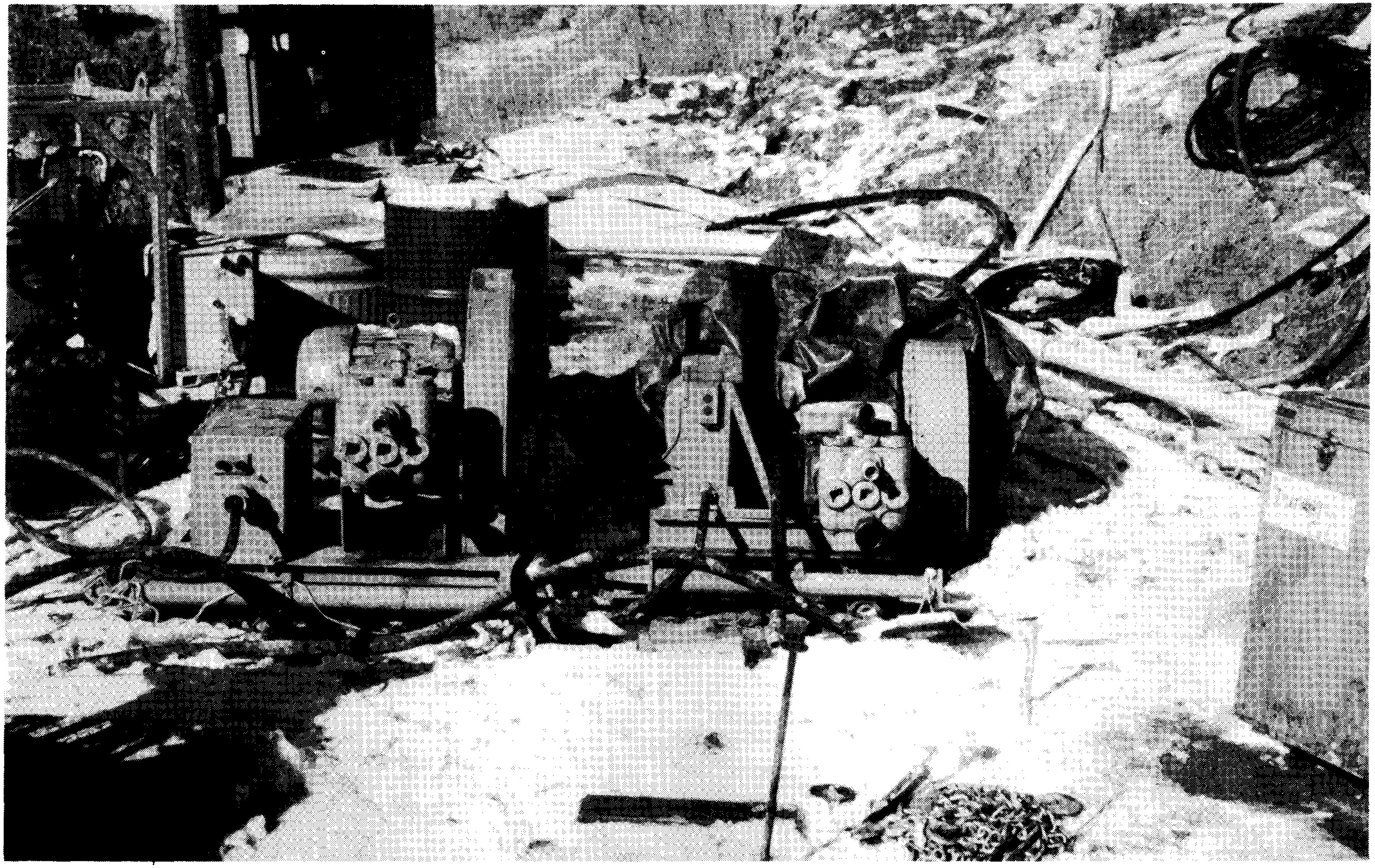


Figure 26. – Triple piston pumps.

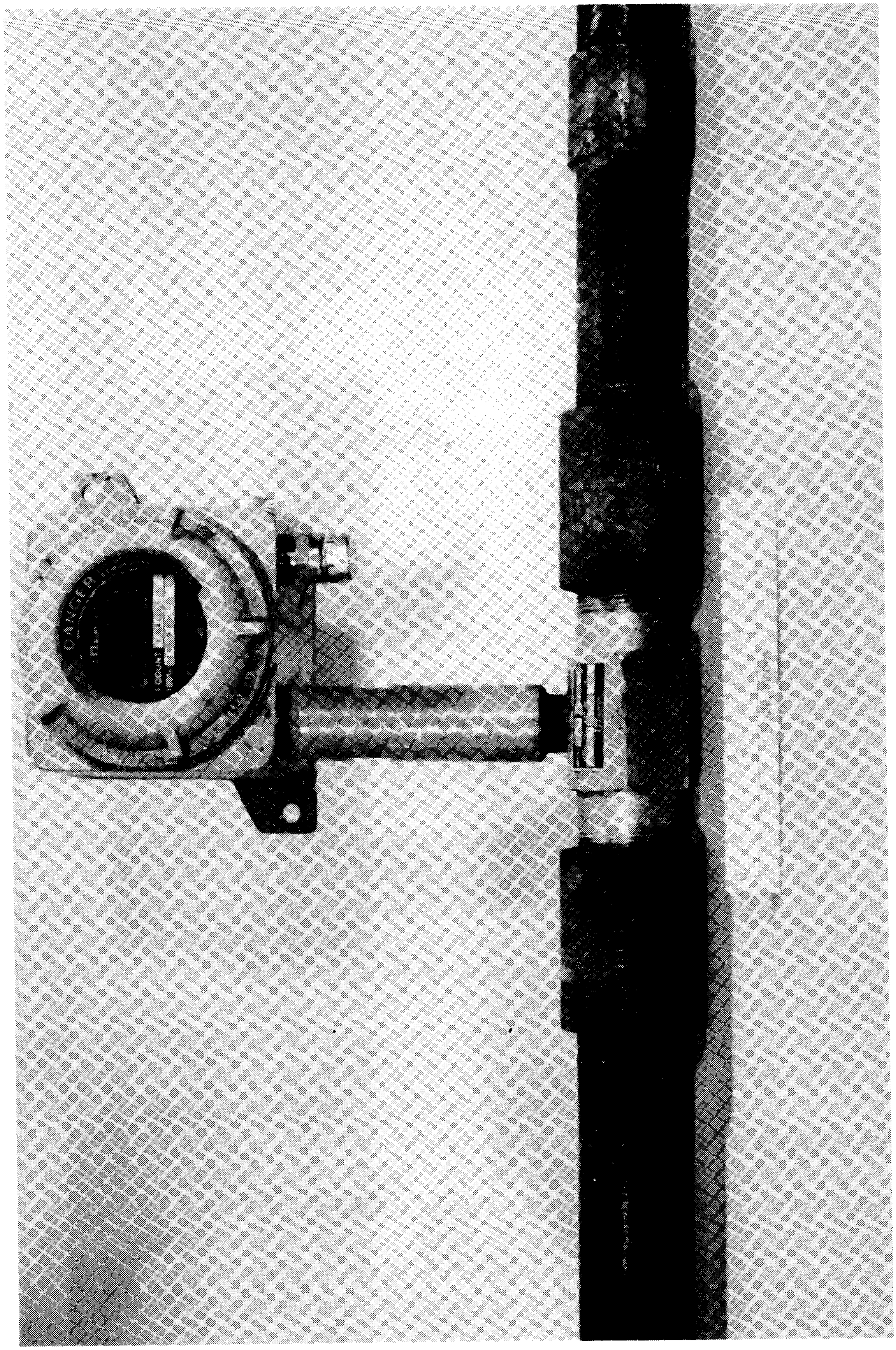


Figure 27. – Barton flowmeter and totalizer.

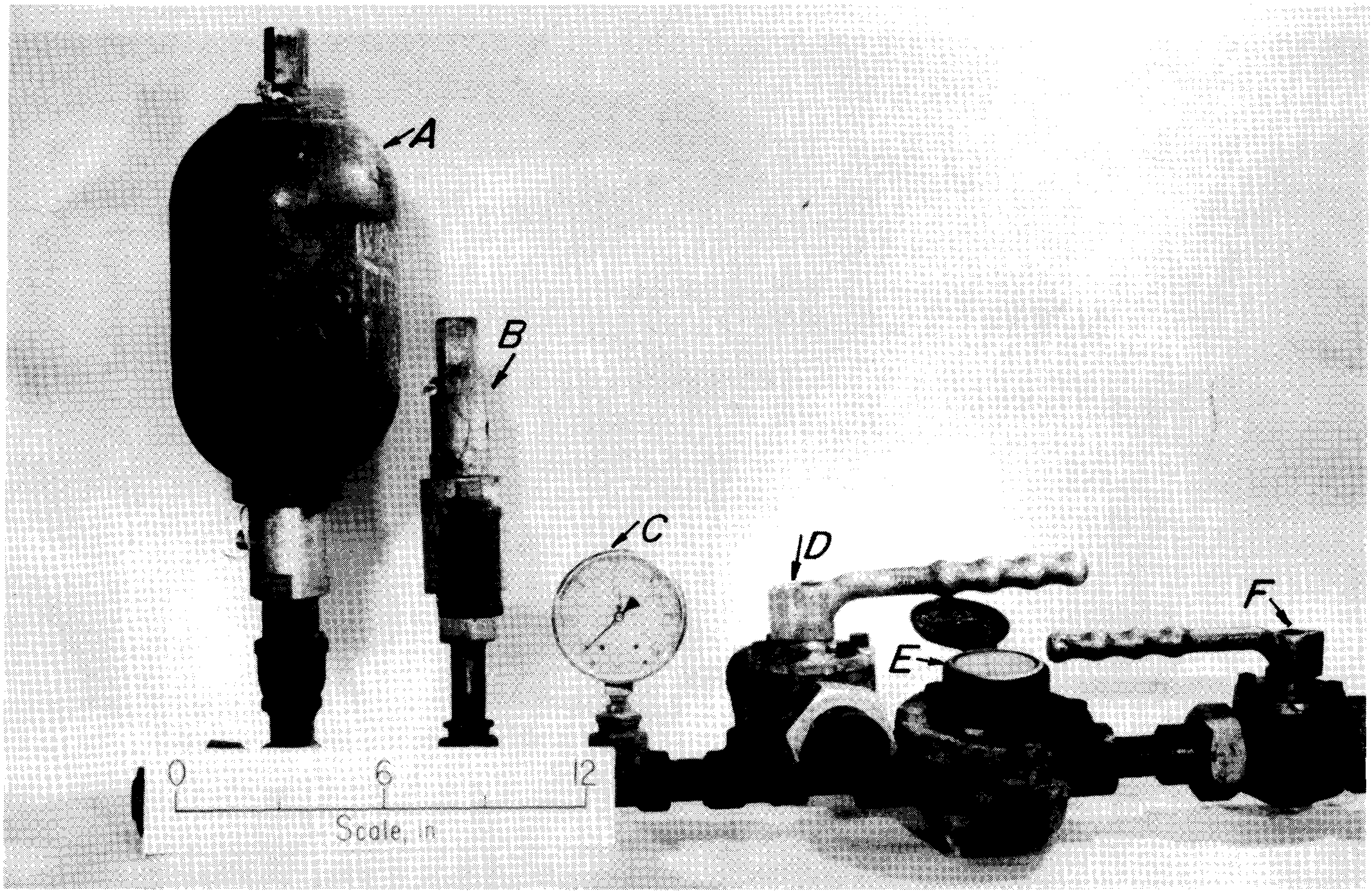


Figure 28. – Water handling equipment. Pulsator, relief valve, intake water pressure gauge, bypass valve, mechanical cumulative flow meter, control valve (left to right) (only one set-up shown, two actually used, one for each pump).

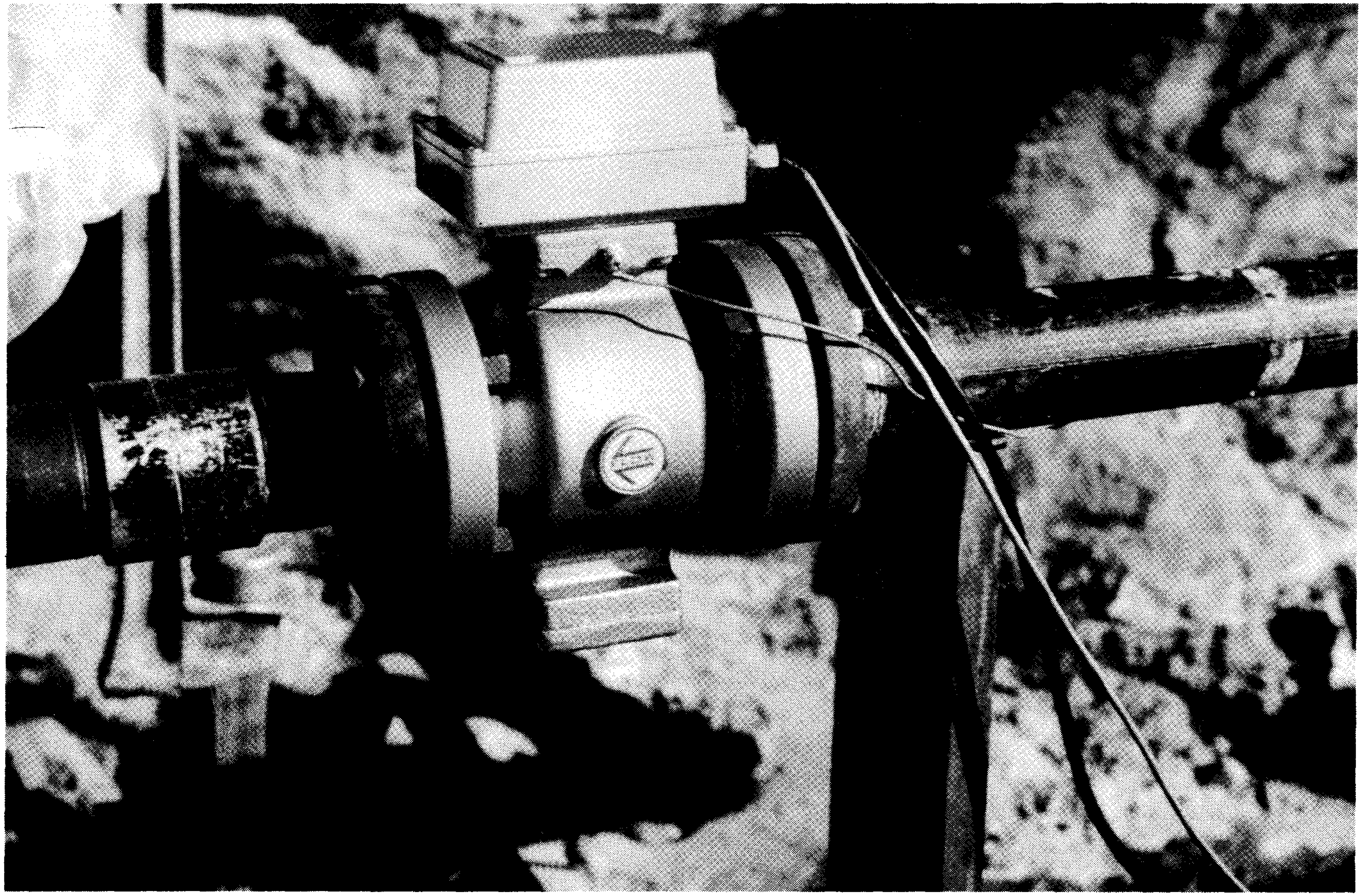


Figure 29. – Nusonics electromagnetic flow meter.

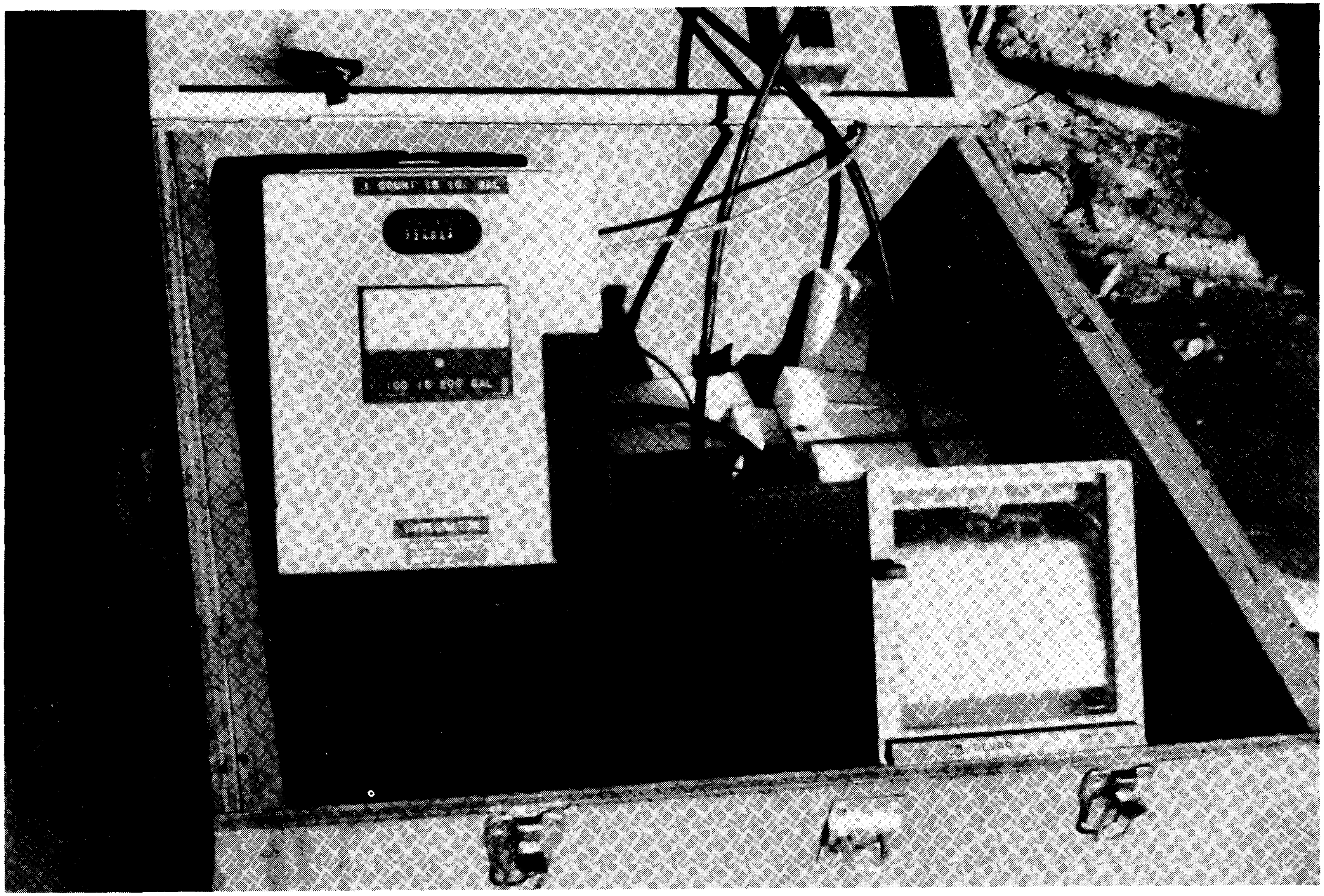


Figure 30. – Devar totalizer and strip-chart recorder.

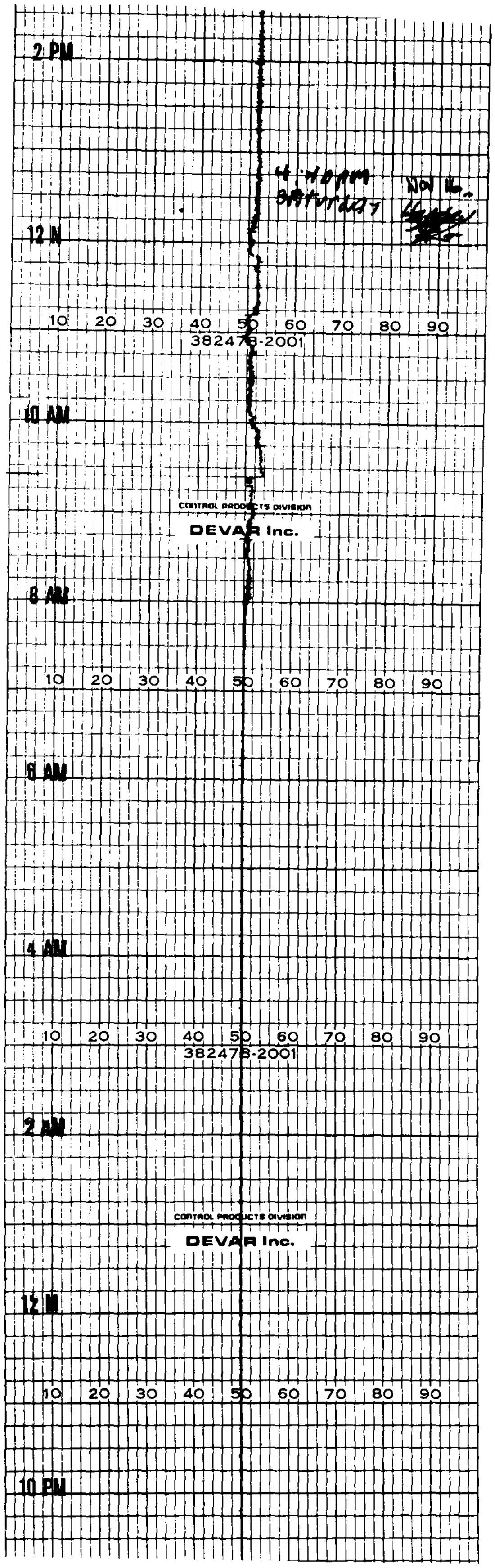


Figure 31. – Recording water flow produced from borehole. (Note that flow recorded is one-half actual flow.)

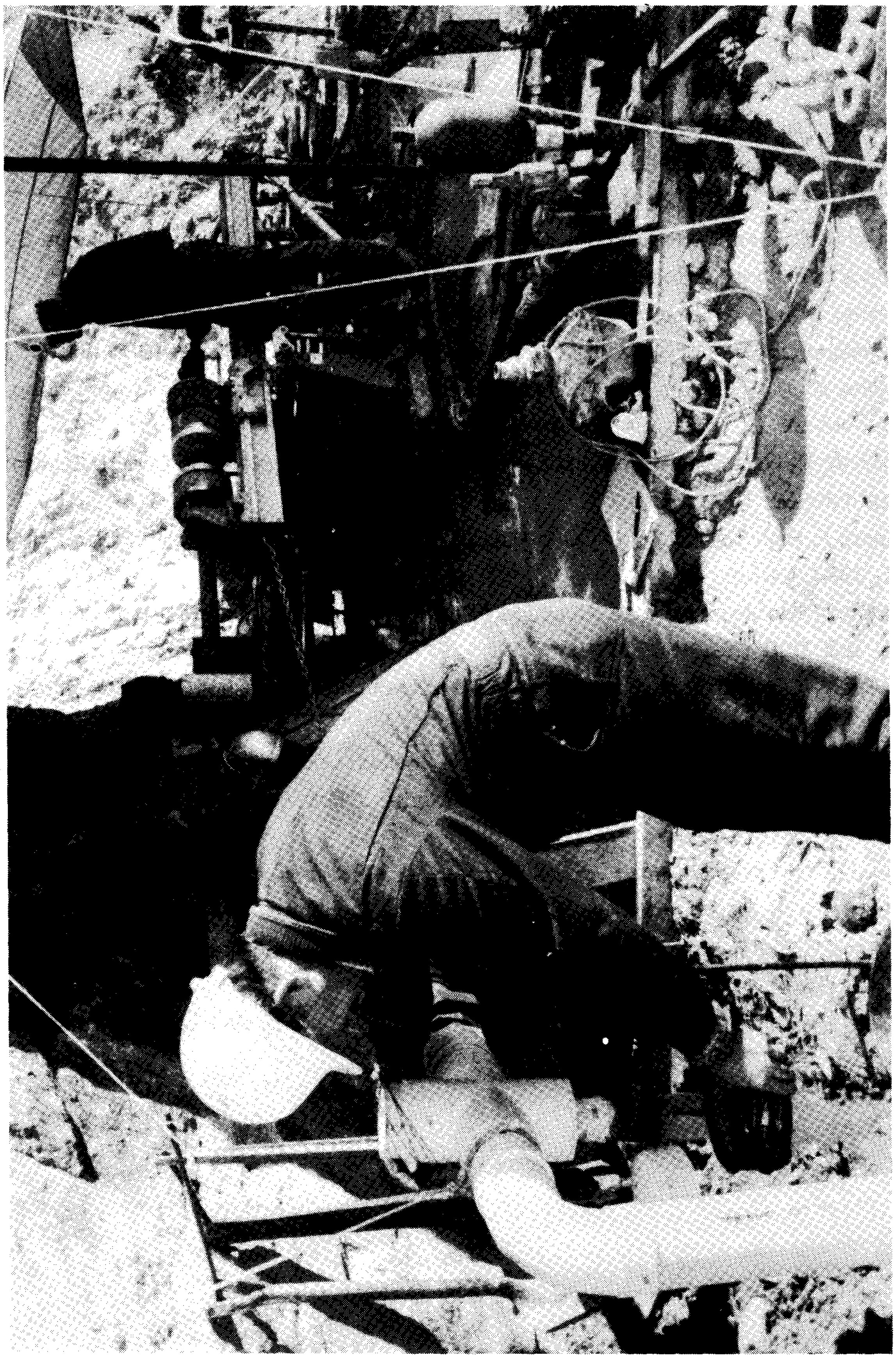


Figure 32. – Sampling cuttings.

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APPENDIX A

LOG OF DIRECTIONAL DRILLING PARAMETERS

Table A.1 – Log of directional drilling parameters.

Date, 1985	Borehole depth, ft	Intake water, gpm	Intake water press., psig	Bit rotation, r/min	Bit torque, ft·lbf	Thrust pressures, bars	Thrust[1] force, lbf	Drill time, 10 ft rod, min	Survey time, min	Comments
September:										
19..........										3½-in reamed to 6-in-ID
October:										
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	Regain 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	"
23..........	245	65	550	785	95	230	4,287	8	25	"
23..........	255	65	575	785	100	235	4,380	6	54	"
23..........	265	65	575	785	100	240	4,474	4	47	"
23..........	275	65	575	785	100	240	4,474	3	13	"
23..........	285	65	550	785	95	240	4,474	3	24	"
24	295	66	700	800	125	245	4,567	3	24	"
24	305	65	625	785	110	248	4,622	4	30	"
24	315	65	575	785	100	250	4,660	4	45	"
24	325	68	575	825	100	250	4,660	3	26	Return water flow increase
24	335	67	575	813	100	248	4,622	4	34	"
24	345	68	575	825	100	245	4,567	3	90	"
24	355	67	600	813	110	245	4,567	3	31	"
24	365	67	600	813	110	245	4,567	4	33	Output flow exceeds input

Table A.1 – Log of directional drilling parameters – Continued.

Date, 1985	Borehole depth, ft	Intake water, gpm	Intake water press., psig	Bit rotation, r/min	Bit torque, ft·lbf	Thrust pressures, bars	Thrust[1] force, lbf	Drill time, 10 ft rod, min	Survey time, min	Comments
October:										
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										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	
November:										
1										Sidetracked at 289 ft
4										Installed 2° w/shoe
5										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										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	

Table A.1 – Log of directional drilling parameters – Continued.

Date, 1985	Borehole depth, ft	Intake water, gpm	Intake water press., psig	Bit rotation, r/min	Bit torque, ft·lbf	Thrust pressures, bars	Thrust[1] force, lbf	Drill time, 10 ft rod, min	Survey time, min	Comments
November:										
9	475	66	550	800	95	300	5,592	5	22	
11..........	485	66	550	800	95	300	5,592	6	90	Problems surveying
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	Conducted 2 surveys
11..........	515	64	525	771	90	300	5,592	5	22	
11..........	525	65	550	785	95	310	5,778	8	69	Conducted 2 surveys
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	Conducted 2 surveys
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	Conducted 2 surveys
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 come-a-long, + 1,000 lb
16..........	785	67	450	813	80	320	5,965	20	20	"
16..........	795	65	480	785	85	320	5,965	20	30	"
18..........	805	65	425	785	75	320	5,965	16	27	"
18..........	815	66	475	800	80	320	5,965	15	21	"

Table A.1 – Log of directional drilling parameters – Continued.

Date, 1985	Borehole depth, ft	Intake water, gpm	Intake water press., psig	Bit rotation, r/min	Bit torque, ft·lbf	Thrust pressures, bars	Thrust[1] force, lbf	Drill time, 10 ft rod, min	Survey time, min	Comments
November:										
18..........	825	66	500	800	90	320	5,965	13	27	Used a come-a-long,+ 1,000 lb
18..........	835	66	500	800	90	320	5,965	11	30	"
18..........	845	66	480	800	80	320	5,965	11	33	"
18..........	855	65	470	785	80	320	5,965	13	22	"
18..........	865	65	450	785	75	320	5,965	12	26	"
18..........	875	65	460	785	75	320	5,965	14	33	"
18..........	885	65	470	785	80	320	5,965	11	27	"

[1] Thrust force = Thrust pressure (bars) × 14.7 psig/bar × 1.268 in^2 (piston area).

APPENDIX B

DEMONSTRATION BOREHOLE SURVEY LOG AND LOG OF DESIRED DEPARTURES

Table B.1 – Demonstration borehole survey log and log of desired departures.

Borehole depth, ft	Survey depth, ft	Borehole inclina-tion, °	Azimuth (uncor-rected),°[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]	Corre-sponding depth, ft[4]
	0	90.0					52,697.79	19,567.69	−5,933.53	52,697.79	0
	6	87.9				0.11			−5,933.42	52,697.42	10
	16	88.0	350.81	0.39	15.99	0.36	52,698.18	19,583.68	−5,933.06	52,698.06	20
	26	87.5				0.39			−5,932.67	52,698.19	30
	36	88.9				0.31			−5,932.36	52,698.32	40
65	49	88.9	349.50	1.24	32.96	0.19	52,699.42	19,616.64	−5,932.17	52,698.45	50
75	59	89.5	348.25	0.15	9.99	0.14	52,699.57	19,626.64	−5,932.03	52,590.58	60
85	69	90.0	348.50	0.06	9.99	0.04	52,699.64	19,636.64	−5,931.99	52,698.72	70
95	79	90.4	350.50	0.26	9.99	−0.03	52,699.90	19,646.63	−5,932.02	52,698.85	80
105	89	90.9	351.50	0.52	9.98	−0.11	52,700.42	19,656.62	−5,932.14	52,698.98	90
115	99	91.0	352.86	0.73	9.97	−0.17	52,701.15	19,666.59	−5,932.30	52,699.11	100
125	109	91.4	350.70	0.66	9.97	−0.21	52,701.81	19,676.57	−5,932.51	52,699.25	110
135	119	91.0	351.20	0.51	9.98	−0.21	52,702.33	19,686.55	−5,932.72	52,699.38	120
145	129	90.5	351.00	0.54	9.98	−0.13	52,702.87	19,696.54	−5,932.85	52,699.51	130
155	139	90.6	348.90	0.31	9.99	−0.10	52,703.18	19,706.53	−5,932.95	52,699.64	140
165	149	90.7	349.50	0.17	9.99	−0.11	52,703.35	19,716.53	−5,933.06	52,699.78	150
175	159	91.0	348.47	0.17	9.99	−0.15	52,703.52	19,726.53	−5,933.21	52,699.91	160
185	169	91.5	350.36	0.25	9.99	−0.22	52,703.77	19,736.52	−5,933.43	52,700.04	170
195	179	89.7	347.70	0.18	9.99	−0.10	52,703.95	19,746.52	−5,933.53	52,700.17	180
205	189	89.2	347.90	−0.03	9.99	0.10	52,703.91	19,756.52	−5,933.44	52,700.30	190
215	199	89.5	348.40	0.03	9.99	0.11	52,703.94	19,766.52	−5,933.33	52,700.44	200
225	209	89.9	348.70	0.10	9.99	0.05	52,704.04	19,776.51	−5,933.27	52,700.57	210
235	219	90.0	348.00	0.06	9.99	0.01	52,704.10	19,736.51	−5,933.26	52,700.70	220
245	229	90.1	345.70	−0.20	9.99	−0.01	52,703.90	19,796.51	−5,933.27	52,700.83	230
255	239	90.0	347.00	−0.29	9.99	−0.01	52,703.61	19,806.51	−5,933.28	52,700.96	240
265	249	90.0	345.50	−0.31	9.99	0.00	52,703.30	19,816.50	−5,933.28	52,701.10	250
275	259	90.5	346.30	−0.37	9.99	−0.04	52,702.94	19,826.50	−5,933.32	52,701.23	260
285	269	91.1	344.80	−0.43	9.99	−0.14	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

Table B.1 – Demonstration borehole survey log and log of desired departures – Continued.

Borehole depth, ft	Survey depth, ft	Borehole inclination, °	Azimuth (uncorrected),°[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]
305	289	92.1	347.10	0.31	9.99	−0.33	52,701.69	19,856.46	−5,934.04	52,701.62	290
315	299	92.5	346.00	−0.25	9.99	−0.40	52,701.43	19,866.44	−5,934.44	52,701.75	300
325	309	93.0	345.35	−0.41	9.98	−0.48	52,701.03	19,876.42	−5,934.92	52,701.88	310
335	319	93.5	345.10	−0.48	9.97	−0.57	52,700.54	19,886.40	−5,935.49	52,702.01	320
345	329	93.9	345.10	−0.50	9.97	−0.65	52,700.04	19,896.36	−5,936.13	52,702.14	330
355	339	94.3	344.95	−0.52	9.96	−0.72	52,699.52	19,906.32	−5,936.85	52,702.27	340
365	349	94.9	345.10	−0.52	9.95	−0.80	52,699.01	19,916.28	−5,937.65	52,702.40	350
375	359	98.0	344.95	−0.52	9.92	−1.12	52,698.49	19,926.20	−5,938.77	52.702.53	360
385	369	95.5	342.55	−0.74	9.90	−1.18	52,697.75	19,936.10	−5,939.95	52,702.66	370
395	379	94.9	345.61	−0.68	9.93	−0.91	52,697.07	19,946.03	−5,940.86	52,702.79	380
405	389	94.8	347.01	−0.29	9.95	−0.85	52,696.78	19,955.99	−5,941.70	52,702.92	390
415	399	95.1	347.34	−0.14	9.96	−0.86	52,696.63	19,965.95	−5,942.57	52,708.05	400
425	409	95.6	346.94	−0.15	9.96	−0.93	52,696.48	19,975.91	−5,943.50	52,703.18	410
435	419	96.0	346.54	−0.22	9.95	−1.01	52,696.26	19,985.85	−5,944.51	52,703.51	420
445	429	96.5	345.08	−0.38	9.93	−1.09	52,695.89	19,995.79	−5,945.60	52,703.44	430
455	439	96.8	345.34	−0.48	9.92	−1.16	52,695.40	20,005.71	−5,946.75	52,703.57	440
465	449	96.8	344.41	−0.54	9.91	−1.18	52,694.86	20,056.62	−5,947.94	52,703.70	450
475	459	97.5	343.62	−0.69	9.90	−1.24	52,694.17	20,025.52	−5,949.18	52,703.83	460
485	469	98.2	343.48	−0.77	9.88	−1.37	52,693.40	20,035.40	−5,950.55	52,703.96	470
495	479	99.6	342.55	−0.85	9.84	−1.55	52,692.54	20,045.24	−5,952.10	52,704.09	480
(5)											
	89	90.9	351.50				52,700.42	19,656.62	−5,932.14	52,698.98	90
	99	91.0	352.50	0.70	9.97	−0.17	52,701.12	19,666.59	−5,932.31	52,699.11	100
	129	90.9	352.00	2.22	29.91	−0.50	52,703.34	19,696.51	−5,932.80	52,699.51	130
	159	90.7	352.00	2.09	29.92	−0.42	52,705.43	19,726.43	−5,933.22	52,699.91	160
	189	89.2	350.00	1.57	29.96	0.03	52,707.00	19,756.39	−5,933.20	52,700.30	190
	219	90.0	348.50	0.65	29.99	0.21	52,707.66	19,786.38	−5,932.99	52,700.70	220
	249	90.5	348.00	0.13	29.99	0.13	52,707.79	19,816.38	−5,933.12	52,701.10	250

Table B.1 – Demonstration borehole survey log and log of desired departures – Continued.

Borehole depth, ft	Survey depth, ft	Borehole inclination, °	Azimuth (uncorrected),°[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]
	279	91.7	345.00	−0.78	29.98	−0.58	52,707.00	19,646.36	−5,933.70	52,701.49	280
305	289	92.2	344.40	−0.58	9.98	−0.34	52,706.43	19,856.34	−5,934.04	52,701.62	290
315	299	93.9	344.50	−0.62	9.97	−0.53	52,705.81	19,866.30	−5,934.57	52,701.57	300
325	309	96.2	342.50	−0.83	9.93	−0.88	52,704.99	19,876.23	−5,935.45	52,701.88	310
335	319	98.9	342.70	−0.98	9.86	−1.31	52,704.01	19,886.09	−5,936.76	52,702.01	320
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	0.38	9.82	−1.85	52,703.93	19,905.75	−5,940.33	52,702.27	340
365	349	99.9	349.60	0.53	9.83	−1.76	52,704.46	19,915.58	−5,942.09	52,702.40	350
375	359	98.2	344.40	−0.17	9.87	−1.57	52,704.29	19,925.45	−5,943.67	52,702.53	360
385	369	100.3	347.50	−0.35	9.86	−1.61	52,703.93	19,935.31	−5,945.27	52,702.66	370
395	379	103.5	351.20	0.23	9.78	−2.06	52,704.16	19,945,09	−5,947.34	52,702.79	380
405	389	102.9	352.50	0.65	9.71	−2.28	52,704.82	19,954.80	−5,949.62	52,702.92	390
415	399	100.9	346.70	0.27	9.78	−2.06	52,705.09	19,964.58	−5,951.68	52,703.05	400
425	409	101.0	346.70	−0.22	9.81	−1.90	52,704.87	19,974.39	−5,953.58	52,703.18	410
435	419	100.0	346.80	−0.21	9.83	−1.83	52,704.65	19,984.22	−5,955.41	52,703.31	420
445	429	100.0	346.50	−0.23	9.84	−1.75	52,704.42	19,994.07	−5,952.14	52,703.44	430
455	439	100.0	343.30	−0.53	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	−0.85	9.72	−2.16	52,699.00	20,042.80	−5,966.71	52,704.09	480
505	489	102.8	346.30	−0.42	9.74	−2.24	52,689.58	20,052.53	−5,968.95	52,704.22	490
515	499	102.1	347.60	−0.18	9.76	−2.16	52,698.40	20,062.30	−5,971.10	52,704.35	500
525	509	102.9	348.70	0.03	9.76	−2.16	52,698.43	20,072.06	−5,973.26	52,704.48	510
535	519	103.5	350.00	0.23	9.73	−2.28	52,698.65	20,081.80	−5,975.55	52,705.61	520
545	529	103.5	354.90	0.75	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	0.81	9.76	−2.03	52,701.26	20,110.93	−5,982.16	52,706.00	550
575	559	101.0	355.00	0.96	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	0.99	9.77	−1.87	52,705.52	20,150.00	−5,989.60	52,706.52	590
615	599	101.4	353.20	0.94	9.77	−1.93	52,706.46	20,159.77	−5,991.52	52,706.65	600
625	609	101.0	350.50	0.66	9.79	−1.94	52,707.12	20,169.56	−5,993.46	52,706.78	610

Table B.1 – Demonstration borehole survey log and log of desired departures – Continued.

Borehole depth, ft	Survey depth, ft	Borehole inclination, °	Azimuth (uncorrected),°[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]
635	619	100.5	347.00	0.13	9.82	−1.86	52,707.24	20,179.38	−5,995.33	52,706.91	620
645	629	100.2	347.90	−0.09	9.84	−1.80	52,707.15	20,189.21	−5,997.12	52,707.04	630
655	639	100.8	348.70	0.05	9.83	−1.82	52,707.20	20,199.05	−5,998.95	52,707.17	640
665	649	101.5	349.80	0.21	9.81	−1.93	52,707.42	20,208.85	−6,000.88	52,707.30	650
675	659	100.9	350.10	0.33	9.80	−1.94	52,707.75	20,218.67	−6,002.82	52,707.43	660
685	669	100.2	350.70	0.41	9.82	−1.83	52,708.16	20,228.48	−6,004.65	52,707.56	670
695	679	98.9	350.00	0.40	9.80	−1.66	52,708.57	20,238.33	−6,006.31	52,707.69	680
705	689	99.5	349.50	0.30	9.87	−1.60	52,708.87	20,248.20	−6,007.91	52,707.82	690
715	699	100.1	348.40	0.16	9.85	−1.70	52,709.03	20,258.05	−6,009.61	52,707.95	700
725	709	98.9	344.40	−0.28	9.86	−1.65	52,708.76	20,267.91	−6,011.26	52,708.08	710
735	719	99.5	344.20	−0.64	9.85	−1.60	52,708.12	20,277.76	−6,012.86	52,708.21	720
745	729	100.1	345.00	−0.58	9.84	−1.70	52,707.53	20,287.60	−6,014.56	52,708.34	730
755	739	101.0	346.50	−0.38	9.82	−1.83	52,707.15	20,297.42	−6,016.39	52,708.47	740
765	749	102.1	350.60	0.09	9.79	−2.00	52,707.24	20,307.22	−6,018.40	52,708.60	750
775	759	101.4	352.10	0.57	9.77	−2.04	52,707.81	20,316.99	−6,020.43	52,708.73	760
785	769	101.2	353.40	0.81	9.77	−1.96	52,708.63	20,326.76	−6,022.39	52,708.86	770
795	779	100.0	347.50	0.42	9.82	−1.84	52,709.05	20,336.58	−6,024.23	52,708.99	780
805	789	100.1	348.40	0.00	9.84	−1.74	52,709.04	20,346.42	−6,025.98	52,709.12	790
815	799	100.1	348.60	−0.09	9.84	−1.75	52,709.13	20,356.27	−6,027.73	52,709.25	800
825	809	101.2	350.10	0.23	9.82	−1.85	52,709.37	20,366.09	−6,029.58	52,709.38	810
835	819	102.2	352.80	0.59	9.77	−2.03	52,709.45	20,375.86	−6,031.61	52,709.51	820
845	829	103.1	351.60	0.71	9.73	−2.19	52,710.60	20,385.60	−6,033.80	52,709.64	830
855	839	103.3	348.60	0.36	9.73	−2.20	52,711.02	20,395.32	−6,036.08	52,709.77	840
865	849	103.8	349.70	0.19	9.72	−2.34	52,711.22	20,405.04	−6,038.42	52,709.90	850
875	859	104.1	347.50	0.10	9.70	−2.41	52,711.32	20,414.75	−6,040.83	52,710.03	860
885	869	104.1	347.00	−0.18	3.68	−3.41	52,711.14	20,428.32	−6,044.24	52,710.16	870
885	885	103.8	345.60	−0.35	1.64	−2.89	52,710.80	20,439.96	−6,047.14	52,710.29	880

[1] Borehole bearing converted to uncorrected azimuth, radius of curvature calculator program. Corrects for magnetic declination, (Navajo Dam, add 12 degrees East 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 degrees.
[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, used original surveys 07.89 ft.

APPENDIX C

RADIUS OF CURVATURE CALCULATOR PROGRAM

Table C.1 – Radius of Curvature Surveying Program[1,2], HP15C Calculator

LABELS	MEMORY REGISTERS: FREE	USED IN PROGRAM: TEMPORARY STORAGE			USED IN PROGRAM: PERMANENT STORAGE	
A- ΘInew ENTRY						
B- ΘBnew ENTRY	RI	R2-Yproj	R7-ΔDEP	R.0-MD	R.6- ΘInew
C- MEAS DEPTH ENTRY	RO	R3-Xproj	R8-ΔLAT	R.1-Θdec	R.7- DEP
D- COMP. AND OUTPUT	R1	R6-MD	R9-ΔTVD	R.2-Θproj	R.8- LAT
E- INITIAL DATA INPUT				R.3-ΘBold	R.9- TVD
				R.4-ΘBnew	R4 - DEPcollar
				R.5-ΘIold	R5 - LATcollar

PROGRAM LISTING

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1   f LBL A      33  −          65  STO 6      97  SIN        129 X<>Y       161 SIN
2   STO . 6      34  CHS        66  g ABS      98  −          130 f→REC      162 STO X 7
3   g RTN        35  STO 7      67  g PI       99  STO X 8    131 STO 3      163 RCL . 4
4   f LBL B      36  STO 8      68  g TEST7    100 f LBL 4    132 X<>Y       164 COS
5   RCL . 1      37  STO 9      69  GTO 6      101 RCL 9      133 STO 2      165 STO X 8
6   +            38  RCL . 6    70  2          102 STO +.9    134 RCL 7      166 GTO 4
7   STO . 4      39  RCL . 5    71  X          103 RCL 8      135 R/S        167 f LBL E
8   3            40  −          72  RCL 6      104 STO +.8    136 RCL 8      168 R/S
9   6            41  f→RAD      73  g TEST1    105 RCL 7      137 R/S        169 STO . 9
10  0            42  g X=0      74  GTO 5      106 STO +.7    138 RCL 9      170 R↓
11  g TEST7      43  GTO 1      75  +          107 RCL . 4    139 R/S        171 STO . 8
12  GTO 8        44  STO ÷ 7    76  STO 6      108 STO . 3    140 RCL . 7    172 R↓
13  −            45  STO ÷ 8    77  GTO 6      109 RCL . 6    141 R/S        173 STO . 7
14  STO . 4      46  STO ÷ 9    78  f LBL 5    110 STO . 5    142 RCL . 8    174 R/S
15  f LBL 8      47  RCL . 6    79  −          111 RCL . 7    143 R/S        175 STO . 3
16  RCL . 4      48  SIN        80  CHS        112 RCL 4      144 RCL . 9    176 R↓
17  g TEST3      49  RCL . 5    81  STO 6      113 −          145 R/S        177 STO . 5
18  GTO 9        50  SIN        82  f LBL 6    114 RCL . 8    146 RCL 3      178 R↓
19  3            51  −          83  RCL 6      115 RCL 5      147 R/S        179 STO . 0
20  6            52  STO X 9    84  g X=0      116 −          148 RCL 2      180 R/S
21  0            53  RCL . 5    85  GTO 3      117 g→POL      149 g RTN      181 STO 5
22  +            54  COS        86  STO ÷ 7    118 X<>Y       150 f LBL 1    182 R↓
23  STO . 4      55  RCL . 6    87  STO ÷ 8    119 g TEST3    151 RCL . 6    183 STO 4
24  f LBL 9      56  COS        88  RCL . 3    120 GTO 7      152 COS        184 R↓
25  g RTN        57  −          89  COS        121 3          153 STO X 9    185 STO . 2
26  f LBL C      58  STO X 7    90  RCL . 4    122 6          154 RCL . 6    186 R↓
27  STO 6        59  STO X 8    91  COS        123 0          155 SIN        187 STO . 1
28  g RTN        60  f LBL 2    92  −          124 +          156 STO X 7    188 g RTN
29  f LBL D      61  RCL . 4    93  STO X 7    125 f LBL 7    157 STO X 8
30  RCL . 0      62  RCL . 3    94  RCL . 4    126 RCL . 2    158 GTO 2
31  RCL 6        63  −          95  SIN        127 −          159 f LBL 3
32  STO . 0      64  f→RAD      96  RCL . 3    128 g ABS      160 RCL . 4
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[1] Program revised 2/14/86.
[2] Program developed by D. C. Oyler, U.S. BuMines.

Table C.2 – User Instructions, Radius of Surveying Curvature Program, HP15C Calculator

INITIALIZATION - ENTRY OF INITIAL VALUES FOR A HOLE.

PRESS KEYS: [f] , [E]
ENTER (In this order): DEPo , LATo, TVDo (Start position coordinates)
PRESS KEY: [R/S]
ENTER (In this order): MDo, θIo, θBo * (Start position survey values)
PRESS KEY: [R/S]
ENTER (In this order): θdec, θproj, DEPcollar, LATcollar
PRESS KEY: [R/S]
INITIALIZATION COMPLETE
(* Corrected for declination)

TO ENTER A SINGLE SURVEY: (May be done in any order)

ENTER θInew
PRESS KEYS: [f] , [A]

ENTER θBnew *
PRESS KEYS: [f] , [B]

ENTER MDnew
PRESS KEYS: [f] , [C]

(* Must be uncorrected if a declination correction has been entered during initialization)

TO COMPUTE SURVEY: (Computation takes about 15 seconds)
PRESS KEYS: f , D

TO READ SURVEY OUTPUT:
After computation the first number in the display is ΔDEP.
PRESS KEY: [R/S] , to display ΔLAT
PRESS KEY: [R/S] , to display ΔTVD
PRESS KEY: [R/S] , to display DEP
PRESS KEY: [R/S] , to display LAT
PRESS KEY: [R/S] , to display TVD
PRESS KEY: [R/S] , to display Xproj
PRESS KEY: [R/S] , to display Yproj

SIGN AND ANGLE CONVENTION:

All angles read in decimal degrees and in azimuth (0 to 360 degree) form.
Bearing, θB, is in aziunth (0 to 360 degree) form (example: south is 180 degrees).
Inclination, θI, runs 0 (vertical) to 90 (horizontal) to 180 (drilling up) degrees.
Declination correction, θdec: west is negative and east is positive.
Departure, DEP, is the distance along an east-west line, with east positive.
Latitude, LAT, is the distance along a north-south line, with north positive.
True Vertical Depth, TVD, is a distance up and down, with down being positive.
Measured Depth, MD, is the distance measured along the path of the borehole, by the length of the drill pipe
Projection Angle, proj, is an angle used to create coordinates for drawing cross sections of the borehole in one vertical plane oriented at the azimuth of the projection angle. Xproj and Yproj are the coordinates computed using the Projection Angle.
Xproj is the distance from the collar of the hole to the survey point computed along the line of the Projection Angle.
Yproj is the perpendicular distance from the line of the Projection Angle to the survey point.

Values subscripted with "o" are values at the initial point, generally the collar of the hole. Values subscripted with "collar" are values from the collar of the hole. Values subscripted with "new" indicate current survey locations.

APPENDIX D

SIDE TRACKING WITH THE DOWNHOLE MOTOR FROM 275 TO 289 FT BIT DEPTH

The first step to sidetracking was to pull the downhole motor back to a borehole depth of 275 ft where the sidetrack was to begin. Sidetracks can be started where borehole inclination is close to or greater than 90°; the sidetrack will be worn below the existing borehole. Once the downhole motor was placed where the sidetrack was to begin, a survey was taken so the tool face could be set accurately at 180°. Sidetracking began by completing three 10-ft reaming passes from the beginning of the sidetrack to 10 ft into the sidetrack or new borehole. After the first 10-ft pass was completed, then the drill rod was pulled back; the second pass was completed, followed by the third. Each of the three passes took about 30 min, so as to wear away the bottom side of the borehole slowly and effectively. The downhole motor drilling parameters during reaming were 700- to 1,200-lb thrust and 700 to 800 r/min rotation. From the beginning of the first reaming pass to the end of the third pass, there was a gradual increase in the volume of sandstone cuttings and a darkening in color of the drill effluent, indicating that the bottom side of the borehole was being worn deeper and deeper (fig. D.1). After the third pass, a drill rod was added and the fourth reaming pass was begun. Care was taken to advance the in-hole motor slowly at the start of the fourth pass, to avoid jumping over the kerf worn during the first three passes. If this happened, the face of the kerf would be rounded off and the sidetracking procedure might have to be repeated at another borehole depth. The fourth pass needed to be only 4 ft long to complete the sidetrack (fig. D.1). Thrust levels were increased substantially during the fourth reaming pass to maintain the penetration rates of the first three passes. The decrease in penetration rate in the fourth pass is attributed to binding of the rear end of the downhole motor against the high side of the old borehole during the last 4 ft (fig. D.1). This resistance continued until the 4-ft-long fourth pass was completed and the in-hole motor and bit, which were 14-ft long, occupied the 14-fot sidetrack.

By completion of the fourth reaming pass, the drilling effluent consisted entirely of sandstone cuttings in suspension. Before drilling was resumed, a final check was made to ensure that the sidetrack was successful. All rotation and thrust were shut off. Then the downhole motor was thrust slowly (400 – 500 lb) forward. If a new borehole had been started, the end of the new borehole would be encountered immediately and a rapid increase in thrust pressure observed at the drill. When the test was successful, backward thrust was applied immediately to prevent the drill rod from breaking into the old borehole.

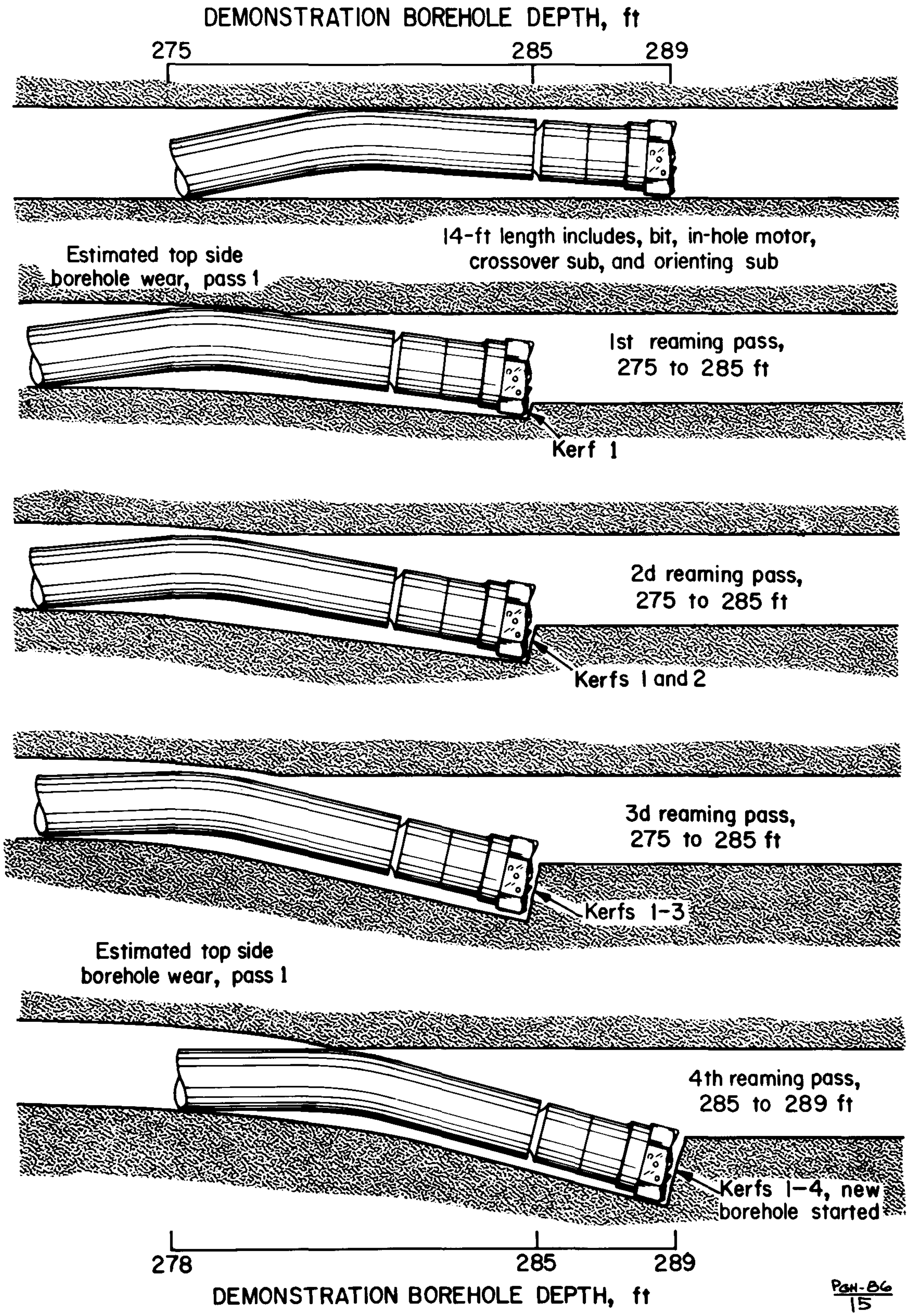

Figure D.1. – Sidetracking with a downhole motor.

APPENDIX E

WATER MEASUREMENT LOG

Table E.1 – Water Measurement Log

DATE 1985	BOREHOLE DEPTH, FT	INTAKE WATER, GAL/MIN	OUTPUT WATER, GAL/MIN	DRILL TIME, MIN	WATER USED DRILLING, GAL	WATER USED DRILLING & FLUSHING, GAL	WATER USED DRILLING, FLUSHING & SURVEYING, GAL	MATERIAL DRILLED	COMMENTS
9-19								C. SAND	3 1/2" HOLE REAMED TO 6"
10-4	45	70	70	9	630	710	780	.	
10-4	55	70	70	5	350	420	490	.	
10-7	65	70	70	5	350	420	490	.	
10-7	75	70	70	11	770	980	1005	.	
10-8	85	70	70	10	700	900	920	.	
10-11	95	70	70	10	700	900	925	.	
10-19	105	65	70	8	520	720	1108	MUD & SAND.	
10-19	115	65	70	8	520	1241	3487	MUD & SAND.	
10-20	125	65	0	6	390	425	503	NO CUTTINGS	LOST CIRCULATION
10-20	135	66	0	7	462	510	556	.	
10-20	145	65	0	12	780	976	1076	.	
10-20	155	65	0	95	975	3000	14809	.	RAN DYE TEST, ROD DRILLE
10-22	165	64	10	7	448	808	914	C. SAND	REGAIN CIRCULATION
10-22	175	65	10	7	455	825	884	.	
10-22	185	65	10	11	715	1014	1313	.	
10-23	195	65	10	10	650	842	902	.	
10-23	205	65	10	8	520	1094	1223	.	
10-23	215	65	20	8	520	856	922	SAND.	COAL
10-23	225	65	20	7	425	659	1739	.	LOST PARTIAL
10-23	235	65	25	9	585	1033	1162	F. SAND.	.
10-23	245	65	30	8	520	2485	2485	.	
10-23	255	65	30	6	390	1330	1411	C. SAND	LOST PARTIAL CIRCULATION
10-23	265	65	33	4	260	1293	1377	.	
10-23	275	65	30	3	195	480	763	.	
10-23	285	65	33	3	195	490	935	.	
10-24	295	66	21	3	198	1496	1732	.	
10-24	305	65	33	4	260	540	946	C. SAND	
10-24	315	65	39	4	260	600	1367	.	
10-24	325	68	50	3	204	859	1074	C. SAND	RETURN WATER FLOW
10-24	335	67	70	4	248	748	875	.	
10-24	345	68	70	3	204	704	859	C. SAND	
10-24	355	67	70	3	201	973	1005	M. SAND	
10-24	365	67	70	4	268	783	913	F & M SAND	OUTPUT FLOW EXCEEDS INPU
10-25	375	67	70	3	201	663	928	.	OUTFLOW > 70 GPM
10-25	385	67	70	4	268	720	859	.	
10-25	395	67	70	4	268	760	920	.	
10-25	405	67	70	4	268	702	847	.	
10-25	415	65	70	5	325	810	910	.	
10-25	425	65	70	6	390	1015	1118	DARK MUDDY	
10-25	435	68	70	3	204	1192	1292	C. SAND	
10-25	445	68	70	3	204	977	877	.	
10-25	455	68	70	4	272	650	938	.	80 GPM OUTFLOW
10-26									INSTALLED 1 DEGREE BEND
10-30	465	63	70	3	189	610	796	C. SAND	
10-30	475	62	70	3	186	580	710	F. SAND	
10-30	485	62	70	3	186	485	674	.	
11-1	495	68	70	3	204	490	667	.	SIDETRACKED AT 289 FT
11-4									SURVEYING PROBLEMS
11-5									INSTALLED 2-DEGREE W/SHO
11-6	305	65	100	21	1365	1493	15172	F. SAND	OUTPUT FLOW > 100 GPM
11-6	315	66	88	28	1848	2020	15065	.	
11-7	325	67	88	13	893	1095	1791	.	
11-7	335	66	88	9	594	710	1013	C. SAND	
11-7	345	66	85	13	858	875	892	.	
11-7	355	65	85	8	520	605	1311	.	
11-7	365	69	85	31	2139	2269	734	.	
11-7	375	65	86	21	1365	1365	2400	.	
11-8	385	67	90	25	1675	1675	1675	.	
11-8									
11-9	395	68	90	5	340	395	5864	.	
11-9	405	66	94	5	330	510	1835	.	
11-9	415	65	94	4	260	463	894	.	
11-9	425	66	94	5	330	500	594	.	
11-9	435	65	94	6	390	765	865	.	
11-9	445	66	98	5	330	510	1645	.	
11-9	455	67	98	5	335	915	965	.	
11-9	465	66	94	6	396	510	873	C. TO M. SAND	
11-9	475	66	96	5	330	442	887	.	

Table E.1 – Water Measurement Log – continued

DATE 1985	BOREHOLE DEPTH, FT	INTAKE WATER, GAL/MIN	OUTPUT WATER, GAL/MIN	DRILL TIME, MIN	WATER USED DRILLING, GAL	WATER USED DRILLING & FLUSHING, GAL	WATER USED DRILLING, FLUSHING & SURVEYING, GAL	MATERIAL DRILLED	COMMENTS
11-11	485	66	94	6	396	510	950	.	
11-11	495	65	94	4	260	510	1800	.	
11-11	505	65	94	7	455	500	1300	.	
11-11	515	64	94	5	320	450	1290	.	
11-11	525	65	95	8	520	720	1280	.	
11-11	535	65	95	7	455	510	1130	.	
11-11	545	65	95	6	390	648	2070	.	
11-13	555	66	95	11	726	900	1030	.	
11-13	565	67	95	6	402	530	1440	.	
11-13	575	67	95	6	402	520	1084	.	
11-13	585	65	95	6	390	451	1316	.	
11-13	595	64	98	5	320	510	1930	.	
11-13	605	67	100	9	603	640	1300	.	
11-14	615	65	100	11	715	794	1110	.	
11-14	625	66	128	10	660	800	1278	.	
11-14	635	66	128	9	594	537	1287	.	
11-14	645	65	128	6	390	455	955	.	
11-14	655	65	128	6	390	579	943	.	
11-14	665	66	128	7	462	557	896	.	
11-15	675	66	100-	15	1050	1217	1659	.	
11-15	685	66	100	7	462	642	1282	C. TO M. SAND	
11-15	695	65	100	15	975	1020	1120	.	
11-15	705	67	100	9	603	746	1387	.	
11-15	715	67	100	6	402	413	1013	.	
11-15	725	67	100	8	536	600	1059	.	
11-15	735	66	100	17	1122	1122	1291	.	
11-16	745	66	100	23	1518	1546	1905	.	
11-16	755	66	100	25	1650	1760	1858	.	
11-16	765	65	100	39	2535	3088	4000	.	
11-16	775	66	100	23	1518	1841	2034	C. TO M. SAND	
11-16	785	67	100	20	1340	1746	2222	.	
11-16	795	65	104	20	1300	1759	2734	.	
11-16	805	65	104	16	1040	1110	1300	.	
11-18	815	66	104	15	990	1100	1284	.	
11-18	825	66	104	13	858	1447	1725	.	
11-18	835	66	104	11	726	1335	1742	.	
11-18	845	66	104	11	726	1680	1754	.	
11-18	855	65	104	13	845	1704	2081	.	
11-18	865	65	104	12	780	1459	1980	.	
11-18	875	65	104	14	910	1102	2035	.	
11-18	885	65	104	11	715	915	1800	.	
TOTALS					63782	98398	180624		
AVG/10FT.					607	937	1720		