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DIRECTIONAL DRILLING AND EQUIPMENT FOR HOT GRANITE WELLS

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ABSTRACT

Directional drilling technology was extended and modified to drill the first well of a subsurface geothermal energy extraction system at the Fenton Hill, New Mexico, hot dry rock (HDR) experimental site. Borehole geometries, extremely hard and abrasive granite rock, and high formation temperatures combined to provide a challenging environment for directional drilling tools and instrumentation.

Completing the first of the two-wellbore HDR system resulted in the definition of operation limitations of many conventional directional drilling tools, instrumentation, and techniques. The successful completion of the first wellbore, Energy Extraction Well No. 2 (EE-2), to a measured depth of 4.7 km (15,300 ft) in granite reservoir rock with a bottomhole temperature of 320°C (610°F) required the development of a new high-temperature downhole motor and modification of existing wireline-conveyed steering tool systems. Conventional rotary-driven directional assemblies were successfully modified to accommodate the very hard and abrasive rock encountered while drilling nearly 2.6 km (8,500 ft) of directional hole to a final inclination of 35° from the vertical at the controlled azimuthal orientation. Data were collected to optimize the drilling procedures for the programmed directional drilling of well EE-3 parallel to, and 370 metres (1,200 ft) above, EE-2.

Drilling equipment and techniques used in drilling wellbores for extraction of geothermal energy from hot granite were generally similar to those that are standard and common to hydrocarbon drilling practices. However, it was necessary to design some new equipment for this program; some equipment was modified especially for this program and some was operated beyond normal ratings. These tools and procedures met with various degrees of success.

Two types of shock subs were developed and tested during this project. However, downhole time was limited, and formations were so varied that analysis of the capabilities of these items is not conclusive. Temperature limits of the tools were exceeded.

Commercial drilling and fishing jars were improved during the drilling program. Three-cone, tungsten-carbide insert bit performance with downhole motors was limited by rapid gauge wear. Rotary drilling was optimized for wells EE-2 and EE-3 using softer (IADS 635 code) bits and provided a balance between gauge, cutting structure, and bearing life. Problems of extreme drill string drag, drill string twist-off, and corrosion control are discussed.

DISCLAIMER

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INTRODUCTION

The Hot Dry Rock (HDR) Geothermal Program of the Los Alamos National Laboratory for extracting heat from crystalline rocks has been developed at Fenton Hill, New Mexico over the past six or seven years. The basic concept for this system requires that two parallel deviated wells be drilled in hot granite and that fractures be made between those wells. Water is then circulated through this system under pressure and heat extracted from the water at the surface before it is returned to the injection well. This type of reservoir system has proven to be feasible with the extraction of heat from two holes drilled to about 3-km (10,000-ft) depth [1]. The Project is now completing the second of another pair of holes in the 4.6-km (15,000-ft) depth range, which have an inclination of 35° to the vertical in an uncased open-hole reservoir section about 1200 m (4,000 ft) long. A sketch of this system is shown in Figure 1.

The construction of an HDR geothermal energy extraction reservoir system at Fenton Hill is rather straightforward from a geometric viewpoint. The technology requires that two slant-type wells be drilled to intersect the resource region with the two wells located in essentially the same vertical plane, a plane that is approximately normal to the fracture planes. In geologic and tectonic situations where the fractures are vertical, as at Fenton Hill, a practical maximum limit is likely placed upon the angle of inclination that can be achieved in very hard rock with modern drilling technology. The length of the inclined section of wellbores and their vertical separation are based upon the possible fracture spacing, power output and reservoir life required, and the vertical wellbore spacing over which a high probability of interconnection can be achieved via hydraulic fracturing. The new Fenton Hill HDR reservoir and drilling geometry is based upon a spacing 10 to 15 vertical fractures having a horizontal separation [2] of 37 to 55 m (120 to 180 ft). A power output capacity of about 30 to 50 MW(t) and a reservoir drawdown of at most 20% in 10-y production should be possible. Based upon the results from the shallower 3-km (10,000-ft) depth HDR system produced at Fenton Hill, a wellbore spacing of 370 m (1200 ft) was planned.

The first well of the new system, energy extraction well No. 2 (EE-2), was spudded April 1979 and reached total depth May 12, 1980. This deeper EE-2 well will be the injection well and has a measured bottom-hole static temperature of about 320°C (610°F). The upper well of the pair, designated as EE-3, was spudded May 16, 1980 and is currently (mid-December 1980) being drilled. Directional operations are in the midst of building the 35° inclination angle of the 31.1 cm (12-1/4-in.) drilled diameter portion of the wellbore. The current depth is about 3.2 km (10,500 ft).

This report focuses on the directional drilling aspects of these two wells and discusses some of the equipment developed and used in the drilling operations and the experience gained in the drilling of EE-2 and EE-3 (to date). Previous drilling experience at Fenton Hill for the 3 km (10,000 ft) deep wells EE-1 and GT-2 can be found in Refs. [3 through 7].

DIRECTIONAL DRILLING

Most of the drilling of the two wells is performed using rotary drilling methods with tungsten-carbide insert-button bits. Blade type stabilizers were initially used in the bottom-hole assemblies (BHA) to keep the hole straight. Because these wore rapidly (Figure 2) in the granitic formations they were replaced by 6-point and 3-point reamers with replaceable rotating rollers. Smooth-faced rollers were used when the reamer was required basically for stabilization, and knobby roller-cutters with tungsten-carbide buttons were used for reaming [8,9]. Standard "fulcum" type lifting assemblies were found quite useful for increasing the inclination of the boreholes during rotary drilling. However, the holes usually walked to the left at unpredictable rates when using rotary drilling for building angle with these assemblies[8]. Downhole drill motor runs were required to correct the direction of the wells. Stabilized straight holes tended to walk either to the right or left depending, presumably, on the formation characteristics. Variations in weight and rotary speed did not appear to have any effect on this tendency.

The granitic formation has a demonstrated tendency to fracture in vertical planes that are expected to run in a north-west/south-east direction. In order to place the wells so that heat extraction might be obtained from the largest volume, the boreholes were directed in a north-easterly direction normal to the anticipated fracture plane and inclined at the maximum feasible angle from the vertical. The largest angle that was thought to be practical with present drilling techniques with a reasonable chance of success was 35°. In addition, the second well (EE-3) was required to be parallel and 370 m (1200 ft) above the first hole (EE-2) with a tolerance of ±30 m (100 ft). These requirements and the unpredictability of rotary directional drilling in the granitic rock, necessitates a plan for a number of downhole motor runs to guide the course of the hole.

The system for changing hole direction with downhole motors is shown in Figure 3 and consists of the bit, downhole motor, bent sub, float sub, mule-shoe sub and non-magnetic drill collars. The steering tool is aligned with the bent sub by means of the mule shoe. The steering tool provides a continuous readout on the rig floor of the orientation from the high side of the hole and allows the portion of the assembly below the bent sub to be turned in the desired direction relative to this reference.

Positive Displacement Motors.

These positive displacement motors (PDM) have long been used in the United States for directional drilling. They consist basically of a helical metal shaft which forms the rotor, and turns in a elastomeric stator. Motors from three suppliers, Table 1A, have been used at Fenton Hill and while they have different performance characteristics they all have temperature limitations which reduce their capabilities for geothermal drilling. In drilling well EE-1, and the present boreholes, we found that the practical maximum limit at which these motors could be used was 200°C (392°F) formation temperature or a depth of 3 km (10,000 ft) in the wells. These motors are constant displacement devices and have the advantage that motor speed is controlled by the drilling fluid flow rate. Other advantages of the PDM motors are availability as rental tools and the fact that PDM reactive torques are fairly predictable and known to directional drilling engineers. This allows preset orientation so that directional changes can be made with the aid of single-shot surveys taken between motor runs. Therefore, PDM operation does not necessarily require the use of the much more expensive continuous reading downhole steering devices.

Three versions of the PDM motors were used in EE-2 and EE-3 drilling, the Smith International's DynaDrill, Christensen's NaviDrill and the Baker Service Tools Motor. With the limited amount of drilling performed with these motors, no definite preferences could be determined; however, the slower rotary speed of the Baker motor resulted in longer bit life.

Turbodrills

A high temperature turbodrill was developed as a joint effort between LASL and Maurer Engineering, Inc. (MEI), Houston, Texas [10]. The general objective of the turbodrill design was to match the turbodrill performance as closely as possible to the bit drilling requirements in granite. Of special inportance were (1) relatively low rotational speed for long bit life, (2) carbide insert bits to be used, (3) short length for downhole eccentric off-set with bent sub, (4) high-torque capability to match bit requirement, and, of course, (5) high-temperature, 300°C (572°F), operating rating. In addition the turbodrill was designed to be maintainable in the field with features such as a replaceable bearing pack.

The as-built performance characteristics of the 19.7-cm- (7-3/4-in.-) diam turbodrill were measured on a dynamometer test stand at the MEI facilities and also while drilling into granite test specimens at the Drilling Research Laboratory (DRL), Salt Lake City, Utah. From the DRL tests an operating map of the turbodrill characteristics was plotted, showing torque, RPM, and penetration rate vs bit weight and fluid flow rate. The DRL tests showed that 31.1-cm (12-1/4-in.) carbide insert bits require approximately 1080 N·m (800 ft-lb_f) torque at 89 kN (20,000 lb_f) bit weight to drill granite, and flow rates of 23 to 25 ℓ/s (370 to 400 gpm) would result in turbodrill rotational speeds of 250 to 350 rpm. The penetration rate determined in the DRL tests drilling in granite increased rapidly as the rotary speed was increased. For example, with 133 kN (30,000 lb_f) bit weight, the drilling rate increased from 1.5 to 7.3 m/h (5 to 24 ft/h) as the rotary speed increased from 50 to 200 rpm. This indicates that relatively high drilling rates can be obtained in granite with the MEI turbodrills but will result in decreased bit life as compared to rotary drilling with the same bit at lower rpm.

In parallel with the development and testing of the 19.7-cm- (7-3/4-in.-) diam turbodrills, a smaller diameter, 13.6-cm- (5-3/8-in.-) diam, turbodrill was developed by MEI and tested in a similar fashion. These 13.6-cm turbodrills have sufficient torque to rotate 22.2-cm- (8-3/4-in.-) diam carbide-insert three-cone bits at bit weight of approximately 89 kN (20,000 lb_f), rotational speeds of 350 rpm, and flow rates of 19 ℓ/s (300 gpm).

Motor Performance Experience

Tables 2 and 3 record a summary of the downhole motor directional runs for EE-2 and EE-3, to date. (Note that the downhole motor designations in Tables 2 and 3 are defined in Table 1.) The PDMs were used to a depth of about 3.0 km (9,800 ft) and a formation temperature of 200°C (400°F). The typical downhole motor assemblies used are presented in Table 4, and the performances of the various motor assemblies are summarized in Table 5. The results of these motor directional assembly runs should be reviewed with the knowledge that a two-joint strand of drill pipe 19 m (62 ft) was usually set up for the directional operations.

As is evident in Tables 2, 3, and 5, all motors provided acceptable penetration rates. Downhole life was often limited by severe bit gauge wear to only 2 to 3 operating hours. Steering tool failures also interupted motor runs in a number of instances.

The MEI 19.7-cm- (7-3/4-in.-) diam turbodrill had its first field use in July 1979 and was used to directionally drill in 21 runs in the high-temperature portion of EE-2. The last run in the drilling sequence was typical of the drilling performance achieved using the turbodrill, and the operating characteristics for this run are shown in Table 6.

Severe bearing wear is a problem with the MEI turbodrill and field use requires that adequate bearing spares be available. Also maintenance of the turbines requires the use of a break-out tool and an experienced mechanic. However, field repair can be performed on these units in an adequate shelter. The downhole running time between servicing of these tools is comparable to that of the PDM's, but bit wear was somewhat greater with the higher speed turbine.

Rotary-Build and Rotary-Hold Results

Following the series of motor-driven directional runs in EE-2 that successfully attained the north-easterly direction of that well, a sequence of angle-built rotary runs was made, see Table 4. These inclination build assemblies were hampered by variable left-walk tendencies. Finally, a strong build assembly achieved the desired 35° inclination.

After reducing the borehole diameter at 3.2 km (10,500 ft) to 22.2 cm (8-3/4-in.) diam the EE-2 inclination was locked-in very effectively with a stiff, packed-hole assembly (Table 4). Although some slight walk tendencies were experienced, the well was drilled to total depth without further directional corrections.

Note that both build and hold assemblies used roller reamers. Although these used as contact tools only provide small contact areas, the roller reamers provided satisfactory directional control. Occasionaly severe wear was experienced, Figure 4.

Several turbine motors have been tested thus far in the EE-2, EE-3 drilling program. Two MEI 13.7-cm- (5-3/4-in.-) diam turbines were tested at the bottom of EE-2 in preparation for possible use in the 22.2 cm (8-3/4-in.) section of EE-3. (See Tables 1C and 2.) Also, two 17.8-cm- (7-in.-) diam DynaDrill (Smith International) directional motor tests (Tables 1C and 3) were conducted. These all-metal DynaDrill directional turbines are also candidates for use for directional corrections in the high-temperature section of EE-3. Two other straight-hole high-temperature DyanDrill turbines (Key DD7TS in Table 1C, and Table 3) were run in EE-3 with limited success due to hole conditions. The DynaDrill turbine runs were supported by the Sandia National Laboratory Geothermal Drilling and Completions R&D Program. It appears that these motors have excellent high-temperature capabilities and will find application in geothermal well directional drilling operations where their performance characteristics (e.g., torque) are applicable.

Steering Devices and Surveying Tools

Magnetic single-shot surveys were taken at intervals to show the wellbore inclination and direction. This information was plotted as the wells progressed to show trajectories so that the well could be guided by directional drilling methods as required. These trajectories are shown in Figures 5 and 6. Standard single-shot units with heat shields were used with standard photographic films furnished by the service companies. However, it was found necessary to replace the "O" rings in the standard units with Viton "O" rings. Also to keep the film from being fogged at high temperature, it was necessary to keep the film and the camera section of the instrument packaged in desicant until immediately prior to assembling it into the instrument. The magnetic single shot data proved to be sufficiently reliable to plot the holes. Single-shot data were taken on a slick line and occasionally by go devil to a depth of about 2740 m (9,000 ft) and then by 16-mm (5/8-in.) sand line below that depth.

Multi-shot surveys were taken to confirm the single-shot data. This method has only limited applicability to very high-temperature wells; however, as films that are currently available are not sufficiently heat resistant to allow delays downhole while obtaining data. Films have been manufactured which have satisfactory heat resistant properties but due to the extremely limited market for this film it was not available for this use.

Three different models of the continuous reading downhole steering tools were used, Table 1. These tools transmit a continuous azimuthal reading (measured from the high side of the hole) to the surface and will provide magnetic azimuthal and inclination readings upon request from the control vehicle. The Scientific Drilling Control (Eye) tool was the only tool that proved adequate to withstand the vibration and the extreme temperatures required. This tool was not required to operate at the bottom of EE-2 but was tested in-hole at the end of the drilling. It was found to be able to withstand a formation temperature of 315°C (600°F) for 6 hours with a heat shield.

The guidance of a borehole with steering tools depends on the alignment of the tool with the bent sub (Figure 3) above the motor and alignment of the tool depends upon the seating of a mule shoe to align it with the alignment sub and consequently the bent sub. This system of alignment generally works quite well but one, and possibly two runs, in well EE-3 were misdirected when the mule shoe was jammed in a position 170° from the correct seating position. See Run No. 31 in Table 3.

Shock Absorbers

Initial testing of the drilling characteristics of granite at the Drilling Research Laboratory, Inc. (DRL), Salt Lake City, Utah, using 31.1-cm- (12-1/4-in.-) diam insert bits indicated that severe vibration and shock conditions existed near the bit at the speeds of the turbodrill operation. A properly designed, high-temperature shock absorber was judged to be needed for turbodrill operations at the Fenton Hill site. Testing of several commercially available shock-absorber tools at DRL confirmed that significant reduction in vibration and shock was possible, but that some design, materials, and performance alterations were necessary for use in conjunction with a turbodrill at geothermal conditions. Requirements were met by two firms, Griffith Oil Tools (Edmonton, Alberta) and Mustang Oil Tools (Corpus Christi, Texas) [11]. Actual application of these tools in EE-2 confirmed enhanced turbodrill performance. This performance was observable in somewhat higher penetration rates, increased bit and turbodrill life, and in reduced steering tool damage. Both shock absorption tools, however, experienced sealing problems at temperatures above about 180°C (350°F) and subsequent turbodrilling runs were performed without a shock absorber tool.

Commercially available shock absorber tools were successfully utilized for all rotary drilling applications at temperatures less than 205°C (400°F). Drilco's (Division of SII) low-temperature rated (rubber) shock tools were used to drill the 66-, 44.5- and 3.1-cm (26, 17-1/2- and 12-1/4-in. holes to a temperature of nearly 150°C (300°F) with the high-temperature rated version (metal) used to a temperature of 205° (400°F). A high-temperature rated shock absorber offered by Houston Engineering, Inc. (Div. of Wilson Ind.) featuring not only axial, but also torsional dampening, is currently being used in the 31.1-cm (12-1/4-in.) hole at temperatures exceeding 200°C (400°F) in the well EE-3.

Drilling and Fishing Jars

During the extensive directional drilling operations conducted below 2134 m (7000 ft) in both wells, a large amount of axial and torsional drag was observed between the drill string and the borehole wall. This phenomena is discussed in detail later. The direct effect however, was to cause normal hoisting and rotating operations to be conducted at stresses very nearly approaching the plastic yield point of the drill string. The implications for drill string sticking due to additional drag forces resulting from a slightly undergauge hole, borehole sloughing, junk in the hole, etc. were potentially disastrous. It was therefore determined early in the drilling operation that it would be necessary to include a set of drilling jars in the upper bottom-hole assembly as a protective measure designed to assist in overcoming sticking forces over and above the background drag forces that might arise in the course of normal drilling activities. To this end, a set of high-temperature mechanical drilling jars was initially included in the drill collar string as the drilling of well EE-2 progressed below 2134 m (7000 ft). However, as the borehole drill string frictional interaction increased to the point where torsional drag was observed at 5 to 10 revolutions of drill string twist, the capability to successfully manipulate these torsionally responsive mechanical drilling jars rapidly degraded. A search was subsequently initiated for a set of axially responsive drilling jars, of any type, which would perform reliably at the bottom-hole temperature, which at that point was in excess of 205°C (400°F). A commerically available, axially responsive, set of hydraulic drilling jars (HYDRA-JAR) was modified by Houston Engineers, Inc. (Div. of Wilson Ind.) to accommodate borehole temperatures to 288°C (550°F). These jars were successfully used for the remainder of the EE-2 well and the EE-3 for drilling to temperatures exceeding 315°C (600°F).

Major fishing operations at temperatures above 205°C (400°F) were successfully conducted using a set of axially responsive mechanical rotary jars (Type J) provided by Bowen Tools, Inc. These jars performed reliably but suffered premature failure during extensive jarring operations due to the thermal failure of internal seals and the subsequent loss of protective lubricant.

Drilling Bits

Three-cone tungsten-carbide insert bit performance while drilling with a downhole motor was predictable, although disappointing. Severe gauge wear at the higher rotational speeds (350 to 700 rpm) significantly restricted the useful downhole life of motor-driven assemblies. Motor drilling offered exceptional penetration rates in the hard, brittle, abrasive granite [7.6 to 15.2 m/h (25 to 50 ft/h) dependent upon the magnitude of applied bit weight of from 1750 to 5250 N/cm (1000 to 3000 lb/in.) of bit diameter] but was limited to only 2 to 4 h of on-bottom drilling time because of the rapid bit gauge degradation. Several instances of motor drilling-induced subgauge hole required subsequent rotary reaming of the borehole before additional drilling could be performed. IADC coded 835 bits (or nonsealed 831 bits) were successfully modified to include more abrasion resistant inserts on the gauge row, and on the shirt tail and shank, to add life to the motor-driven assembly runs.

Typical cutting structure failure was evidenced by rounding, or even flattening, of the tungsten-carbide inserts versus the more common mode of insert breakage as is usually observed on such bits run at high rotational speeds in very hard rock. Roller bearings suffered little under such circumstances with the exception of elastomeric seal failure at bottom-hole temperatures exeeding 177°C (350°F).

In contrast, the bulk of the rotary drilling in the granitic rock at Fenton Hill was accomplished with IADC coded 637, 635, and 738 tungsten-carbide insert bits. Friction bearing and scaled-roller bearing bits were utilized until bottom-hole drilling temperatures exceeded the capability of the bearing seal [approximately 177°C (350°F)] whereupon nonsealed roller-bearing bits were used for the remainder of the drilling to temperatures exceeding 315°C (600°F). Previous drilling efforts on the shallower Phase I system (wells EE-1 and GT-2) at Fenton Hill utilized EADC coded 835 and 838 bits for the bulk of the rotary drilling. Operated with open-flow nozzles at 45 rpm, and 5250 to 7000 N/cm (3000 to 4000 lb_f/in.) of bit diameter resulted in penetration rates of 2.4 to 3.3 m/h (8 to 11 ft/h) and maximum bit life of 50 to 60 h. Considerable attention was therefore given to determining the bit types and operating conditions that would provide a significantly lower cost per unit of hole drilled. Minimum cost per unit of rotary drilling was subsequently obtained for wells EE-2 and EE-3 by operating considerably "softer" IADC code 635 bits at relatively high energy levels. Typical operating parameters of 9625 to 11,375 N/cm (5500 to 6500 lb_f/in.) of bit diameter, 65 to 75 rpm and 520 to 635 W/cm² (4.5 to 5.5 HHP/in.²) of bit area resulted in penetration rates of 6.7 to 7.3 m/h (22 to 24 ft/h) and maximum bit life of 30 to 40 h. Additional testing was performed to determine the maximum bit loading at which hydraulic floundering of the bit occurred. Flounder points were observed at the previously indicated bit loading at values less than 346 to 404 W/cm² (3.0 to 3.5 HHP/in.²). However, 110 to 634 W/cm² (4.5 to 5.5 HHP/in.²) resulted in sufficient hydraulics to allow loading of the bit to well above its bearing capacity.

As previously described, bit failure was primarily one of rapid gauge degradation. The optimum loading conditions resulted in bearing of 60 to 80% of available life and flattening of the inserts to 1/4 to 1/2 their original height by the time the bit gauge had attained an unacceptable value of 10 to 16 mm (3/8 to 5/8 in.) under gauge. A curious phenomena resulting from this work was the observation of a "drilling trend" as the bit inserts rounded and eventually flattened (seldom broken) while drilling the extremely abrasive granitic rock. This phenomena, as generally observed on steel-tooth bits only, allowed many bits to be pulled on a cost per foot minima, a practice that may very well be unique for tungsten-carbide insert bit drilling.

Control of Drill String Drag

The geometry of each of the two subject wells as previously discussed implies that in addition to numerous doglegs of varying magnitudes, a large portion of the rotary drill string is in direct contact with the borehole wall. In fact, in the lower 1220 m (4000 ft) of the string, which usually contains a significant amount of the total string weight, nearly 20% of the weight is applied normal to the borehole wall. Ordinarily these factors would be of only moderate consequence; however, due to the impermeability of the rock matrix, no lubricating filter cake develops on the borehole walls. This results in considerable axial and torsional frictional drag between the drill string and the borehole. The obvious implication is that the use of high wall contact tools such as long strings of large diameter drill collars and fixed blade stabilizers is virtually prohibited. Additionally, the drill string must be sufficiently strong to cope with this abnormally high frictional interaction.

The first attempt to deal with this problem was to utilize roller reamers as wall contact tools in the BHA versus the more common blade or pad-type stabilizers. This action significantly reduced torsional drag and reduced the magnitude of abrasive wear observed while rotary drilling with the latter. Although the roller reamers provided less wall contact area than the blade stabilizers, satisfactory directional control was realized.

The 31.1-cm- (12-1/4-in.-) intermediate-diam boreholes were drilled from approximately 762 m (2500 ft) to the angle built points of 3536 and 3231 m (11,600 and 10,600 ft) with a string of 21 20-cm (8-in.) o.d. drill collars until the torsional drag (measured at the surface) approached the make-up torque of the 12.7-cm (5-in.) o.d. NC50 connections on the drill pipe and the axial drag approached the plastic yield strength of the drill pipe string. At this point the 20-cm (8-in.) o.d. drill collars were replaced with eighteen 17-cm (6-3/4-in.) o.d. drill collars and 21 joints of 12.7-cm (5-in.) o.d. HEVI-WATE (HWDP) drill pipe. As drilling proceeded into the 22.2-cm (8-3/4-in.) hole at 35° from the vertical, the 17-cm (6-3/4-in.) o.d. drill collars were replaced with an additional 12 joints of HWDP. This string of 33 joints of HWDP was used for bit loading during the ramainder of the 22.2 cm (8-3/4-in. hole).

To further reduce the magnitude of axial and torsional drag between the drill string and the borehole, a procedure was developed to alleviate the problem with the addition of a liquid lubricant to the drilling fluid (water). A mixture of modified triglyceride in alcohol (Baroid Div. of NL Ind., TORQ TRIM II) was added to the drilling fluid at a concentration of 5.7 kg/m^3 (2.0 lb/bbl) and the mixture was injected into the borehole in 8 m^3 (50 bbl pills). Although the lubricant slug was eventually circulated from the borehole, sufficient immediate and residual friction reduction was developed to allow drilling and tripping to continue. This method was developed after considerable pilot testing at bottomhole temperatures indicated all other lubricants to be either thermally degradable within a matter o hours or to be essentially ineffective as lubricants at any temperature when mixed with or replacing the clear water drilling fluid.

Control of Drill String Degradation

In consideration of the hostile environment to which it was exposed, drill string performance on well EE-2 and the first 3050 m (10,000 ft) of EE-3 was remarkably good. The most significant factor was the rapid abrasive wear of the drill string both at the tool joints and along the body or tube. Although no downhole failures were attributed to this abnormal wear, some 1800 m (6000 ft) of drill pipe had to be discarded or downgraded due to external wear. Repeated applications of tungsten carbide hardfacing on the tool joints were used to retard the rate of wear.

Four downhole fatigue failures of the drill string occurred during the drilling of the entirety of EE-2 and the first 3050 m (10,000 ft) of EE-3. However, a series of fatigue failures occurred during the drilling of the 3050 to 3200 m (10,000 to 10,500 ft) interval in EE-3. All of these failures were attributed to fatigue crack growth from deeply penetrating, sharp, corrosion pits. These corrosion pits were incurred prior to utilizing the drill string at the Fenton Hill Project. This series of failures however, prompted a complete change-out of drill-pipe strings. In view of the length of directional hole drilled at Fenton Hill, the magnitude and frequency of axial and torsional loading cycles applied to the drill string and the unknown previous fatigue history of this used drill string, the incidence of fatigue failure of this 12.7-cm (5-in.) o.d. drill string is considered low to moderate. Careful attention was paid to the avoidance of high dogleg severity in the upper hole in addition to the utilization of low-yield strength, 517 MPa (75,000 psi), drill pipe for all but the upper 1057 m (3500 ft) of the string.

In consideration of the fact that clear, fresh water was used as a drilling fluid and that the fluid was cooled during each circulation by atmospheric contact, total corrosion rates were kept to a minimum. Oxidation control was the primary effort on both wells as no sour or scaling constituents were apparent in the fluid system. The combination of an amine filming agent, pH control and oxygen scavenging kept corrosion rates to well below 1.0 mpy.

STATUS OF DRILLING

The status of the drilling program for the directional wells EE-2 and EE-3 is summarized in Figures 5 and 6.

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University of California (LASL) or the U.S. Department of Energy to the exclusion of others that may be suitable.

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Table 1.

A. Description of Downhole Directional Motors Used in EE-2 and EE-3

Type	Diam cm	(in.)	Temperature Rating		Length m	(ft)	Supplier	Key
Positive displacement	17.1	(6-3/4)	~175°	(350°F)	6.0	(19.9)	Baker Service Tools Houston, TX	BPNM
Positive displacement	19.7	(7-3/4)	~155°C	(310°F)	6.0	(19.9)	DynaDrill, Smith Int'l., Irvine, CA	DDPDM
Positive displacement	20.3	(8)	~155°C	(310°F)	6.9	(22.6)	Christensen Downhole Tools, Oklahoma City, OK	NPDM
Turbine	19.7	(7-3/4)	~320°C	(610°F)	6.3	(20.7)	Maurer Engineering Inc., Houston, TX	MEIT

B. Turbines Tested in EE-2 and EE-3

Type	Diam cm	(in.)	Temperature Rating		Length m	(ft)	Supplier	Key
Turbine	13.7	(5-3/8)	~320°C	(610°F)	5.7	(18.7)	Maurer Engineering Inc., Houston, TX	MEIT5 (EE-2)
Turbine	17.8	(7)	>370°C	(700°F)	7.2	(23.7)	DynaDrill, Smith Int'l., Irvine, CA	DDT7D EE-3)
Turbine	17.8	(7)	>370°C	(700°F)	11.8	(38.6)	DynaDrill, Smith Int'l., Irvine, CA	DDT7S (EE-3)

C. Steering Tools Used in EE-2 and EE-3.

Sensor Type	Temperature Rating		Service Company	Key
Magnetometer with inclinometer	275°C[b]	(527°F)	Eastman-Whipstock, Houston, TX	DOT
Magnetometer with inclinometer	316°C[b]	(600°F)	Sperry-Sun, Houston, TX	SST
Magnetometer with inclinometer	200°C[c]	(400°F)	Scientific Drilling Controls, Irvine, CA	EYE

[a] Limited by elastomers used in motor drive system.
[b] Requires heat shield.
[c] Run without heat shield up to 200°C (400°F).

Table 2. Summary of directional drilling runs and results for well EE-2 [Note: All runs with 31.1-cm- (12-1/4-in.-) diam bits, except as noted]

Directional Drill Motor Run No.	Drill Motor*	Steering Tool Service*	Bent Sub Angle	Measured Depth, m (ft)[a]	Borehole Deviation**	Distance Drilled,*** m (ft)	Shock Absorber[b]	Remarks
1	MEIT	N.A.	-0-	1497 (4912)	5 3/4°,S64°W	17 (57)	Yes	First field trial of 19.7 cm (7 3/4") dia. MEI turbodrill
2	DDPDM	DOT	2°?	1979 (6492)	4 1/2°,S64°W	-0-	No	
3	DDPDM	DOT	2°?	1986 (6518)	4 1/4°,----	9.0 (26)	No	Steering tool damaged
4	DDPDM	---	2°?	2011 (6597)	3°,----	24 (79)	No	
5	DDPDM	---	2°?	2017 (6619)	4°,----	6.7 (22)	No	
6	DDPDM	---	2°?	2078 (6818)	4 3/4°,N37°W	30.5 (100)	No	
7	BPDM	---	2°	2107 (6914)	5 1/2°,N6°W	14 (45)	No	
8	BPDM	---	1 1/2°	2135 (7003)	5 3/4°,N16°E	27 (89)	No	KOP
9	DDPDM	---	2°?	2360 (7743)	15°,N13°E	16.5 (54)	No	
10	MEIT	DOT	1 1/2°	2538 (8326)	16°,N13°E	17.7 (58)	Yes	All subsequent runs required intermediate reaming of hole
11	MEIT	DOT	1 1/2°	2538 (8328)	----	0.6 (2)	Yes	Considerable operational difficulties experienced from 2.5-2.8 km (8300'-9303') with steering tool
12	MEIT	DOT	1 1/2°	2564 (8414)	16°,N17°E	26 (86)	Yes	
13	MEIT	DOT	1 1/2°	2604 (8545)	13 3/4°,N37°E	40 (131)	Yes	
14	MEIT	DOT	1 1/2°	2613 (8575)	----	9.1 (30)	Yes	
15	MEIT	DOT	1 1/2°	2613 (8757)	----	-0-	Yes	
16	MEIT	DOT	2°	2754 (9035)	----	18.3 (60)	Yes	
17	MEIT	DOT	2°	2754 (9035)	----	-0-	Yes	Turbine would not rotate
18	MEIT	DOT	1 1/2°	2768 (9082)	15°,N34°E	13 (42)	Yes	
19	MEIT	DOT	2°	2800 (9188)	----	32 (106)	Yes	
20	MEIT	DOT	1 1/2°	2838 (9311)	13 1/2°,N40°E	37.5 (123)	Yes	
21	MEIT	DOT	1 1/2°	2854 (9363)	13 1/4°,N42°E	15.8 (52)	Yes	
22	MEIT	DOT/SST[c]	2°	2854 (9363)	----	-0-	Yes	Turbine would not rotate, steering tool failed
23	MEIT	EYE	2°	2885 (9467)	12 1/4°,N44°E	32 (104)	Yes	
24	MEIT	EYE	2°	2900 (9513)	12 1/4°,N44°E	14 (46)	Yes	
25	MEIT	EYE	2°	2905 (9531)	----	5.5 (18)	Yes	Reached temperature limit of shock absorbers
26	MEIT	EYE	2°	2980 (9776)	13°,N59°E	10	No	
27	BPDM	EYE	2°	2997 (9838)	15 1/2°,N74°E	15.5 (51)	No	
28	BPDM	EYE	2°	3002 (9850)	----	3.0 (10)	No	Reached temperature limit of mud motors
29	MEIT	EYE	2°	3021 (9912)	13°,N59°E	19 (62)	No	
30	MEIT	EYE	2°	3059 (10,035)	----	36 (118)	No	
31	MEIT	EYE	1 1/2°	3216 (10,552)	21°,N70°E	38.7 (127)	No	Motor run used to increase inclination
32+	MEIT5+	N.A.[d]	---	4353 (14,282)	35°,N71°E)	3.0+ (10)	No	First 13.7 cm (5 3/8") dia. turbodrill trial run, straight ahead drilling
33+	MEIT5+	N.A.[d]	---	4357 (14,292)	(35°,N71°E)	3.0+ (10)	No	Second 13.7 cm (5 3/8") dia. trubodrill trial run; T.D. of well

*See Key Table I. **See Fig. 5. ***Distance measured along the wellbore.
+Special trials of 13.7 cm (5 3/8") dia. turbodrills with seals; 22.2 cm (8 3/4") dia. bit; in preparation for EE-3 directional drilling.
[a]Depth at end of run [b]Refer to Williams et al, 1979 [11] [c]HADES version
[d]The heat shielded version of the EYE steering tool was successfully evaluated during these trial runs.

Table 3. Summary of directional drilling runs and results for well EE-3 to 3.2 km (10,500 ft) depth [All runs with 31.1-cm- (12-1/4-in.-) diam bits]

Directional Drill Motor Run No.	Drill Motor*	Steering Tool Service*	Bent Sub Angle	Measured Depth, meters feet	Borehole Deviation**	Distance Drilled,*** m (ft)	Remarks
1	BPDM	---	2°	1981 (6520)	9 1/2°N,53°W	23 (76)	Problems with motor
2	BPDM	---	2°	2027 (6649)	14 3/4°N,54°W	39 (129)	Angle building excessively
3	BPDM	EYE	2°	2075 (6809)	14 3/4°N,37°W	30 (99)	Replace bit
4	DDPDM	EYE	2°	2083 (6868)	14 1/2°N,20°W	17.9 (59)	Plugged bit on connection (no float)
5	DDPDM	EYE	2°	2168 (7114)	13°N,23°E	64.3 (211)	Motor quit
6	BPDM	EYE	2°	2216 (7269)	10 1/2°N,43°E	27.4 (90)	Motor stalled
7	BPDM	EYE	2°	2216 (7269)	---	0 (0)	Bit pinched and motor bent, hit ledge GIH
8	NPDM	EYE	2°	2236 (7337)	10 1/2°N,43°E	20.7 (68)	Bit worn
9	NPDM	EYE	2°	2264 (7427)	8 3/4°N,62 1/2°E	27.4 (90)	Bit worn
10	NPDM	EYE	2°	2281 (7482)	7°N,47°E	16.8 (55)	Bit worn, bit 13 mm (1/2") underguage
11	DDT7D	EYE	1 1/2°	2395 (7856)	---	0.3 (1)	Steering tool failed, test run
12	DDPDM	EYE	1 1/2°	2402 (7883)	15 3/4°N,51°E	8.2 (27)	Dull bit
13	DDPDM	EYE	1 1/2°	2409 (7905)	15°N,47°E	6.7 (22)	EYE quit and motor and bit worn out
14	DDPDM	EYE	1 1/2°	2420 (7940)	16°N,51°E	10.7 (35)	Motor quit
15	NPDM	EYE	1 1/2°	2454 (8052)	16 1/4°N,59°E	34.1 (112)	Bit locked up
16	NPDM	EYE	1 1/2°	2457 (8062)	---	3.0 (10)	Could not orient due to torque
17	NPDM	EYE	1 1/2°	2480 (8139)	---	28.0 (92)	Bit cones loose
18	NPDM	EYE	1 1/2°	2490 (8170)	---	3.4 (11)	Motor quit
19	NPDM	EYE	1 1/2°	2519 (8265)	16 1/4°N,87°E	28.9 (95)	Bit locked up
20	DDT7S	---	---	2562 (8407)	17 1/2°N,84°E	0 (0)	Tachometer N.G., motor not rotating, straight hole tool with stabilizer
21	DDT7S	---	---	2562 (8407)	17 1/2°N,84°E	0 (0)	Could not get to bottom, reamed 27 m (90') straight hole tool with stabilizer
22	NPDM	EYE	1 1/2°	3011 (9879)	25 1/2°N,66°E	8.8 (29)	Bit dull
23	NPDM	EYE	1 1/2°	3011 (9879)	25 1/2°N,66°E	0 (0)	Motor wouldn't rotate, reached temperature limit of PDMs
24	DDT7D	EYE	1 1/2°	3053 (10,017)	24°N,72°E	0 (0)	Washout in drill string
25	DDT7D	EYE	1 1/2°	3053 (10,017)	24°N,72°E	0 (0)	Turbine would not rotate
26	MEIT	EYE	1 1/2°	3083 (10,116)	27°N,70°E	30.4 (99)	Bit underguage, build angle attempt
27	MEIT	EYE	1 1/2°	3085 (10,123)	27°N,70°E	2.1 (7)	Turbodrill quit, build angle attempt
28	MEIT	EYE	1 1/2°	3094 (10,150)	29°N,67°E	8.2 (27)	Bit locked up, build angle attempt
29	MEIT	EYE	1 1/2°	3110 (10,204)	27 3/4°N,68°E	16.5 (54)	Bit underguage, build angle attempt
30	MEIT	EYE	2°	3150 (10,334)	27 1/4°N,51°E	9.4 (31)	Motor quit, build angle attempt
31	MEIT	EYE	2°	3163 (10,378)	24 3/4°N,66°E	13.4 (44)	Dropping angle, steering tool seated 170° from key
32	MEIT	EYE	2°	3175 (10,417)	24 3/4°N,66°E	11.9 (39)	EYE failed

*See Key Table 1. **See Fig. 3. ***Distance measured along the wellbore.

Table 4

Typical Bottomhole Assemblies for Directional Drilling in HDR Wells EE-2 and EE-3

BHA for Drill Motor Azimuthal Angle Alteration	BHA for Rotary Inclination Angle Increase[b]	BHA for Rotary Inclination Maintenance[c]
31.1-cm (12-1/4-in.) diam bit	31.1-cm (12-1/4-in.) diam bit	22.2-cm (8-3/4-in.) diam bit
Shock absorber	3-point BH reamer	6-point BH reamer
Drill motor	Crossover sub	17.1-cm (6-3/4-in.) diam short drill collar
Crossover sub	17.1-cm (6-3/4-in.) diam monel drill collar	3-point string reamer
Bent-orienting sub	17.1-cm (6-3/4-in.) diam short drill collar	17.1-cm (6-3/4-in.) diam monel drill collar
20.3-cm (8-in.) diam monel collar	17.1-cm (6-3/4-in.) diam drill collar	3-point string reamer
Twelve 20.3-cm (8-in.) diam drill collars	Crossover sub	Four 17.1-cm (6-3/4-in.) diam drill collars
21 joints HWDP[a]	3-point string reamer	20 joints HWDP[a]
	20.3-cm (8-in.) diam drill collar	Drilling jars
	Ten 20.3-cm (8-in.) diam drill collars	13 joints HWDP[a]
	8 joints HWDP[a]	
	Drilling jars	
	13 joints HWDP[a]	

[a] 12.7-cm o.d., 74.3 kg/m (5-in. o.d., 50 lb/ft).
[b] Build assembly.
[c] Packed-hole (hold) assembly.

Table 5

A. Motor Assembly Performance, EE-2

Motor Type	Number of Runs	Average Duration Per Run (hours)	Average Distance Per Run* m	(ft)	Average ROP Per Run m/h	(Fph)
MEIT	21	2.8	18.2	(59.8)	6.6	(21.6)
DDPDM	6	4.5	16.7	(54.7)	3.7	(12.3)
BPDM	4	7.8	14.9	(48.8)	1.9	(6.2)

B. Motor Assembly Performance, EE-3 to Date

Motor Type	Number of Runs	Average Duration Per Run (hours)	Average Distance Per Run* m	(ft)	Average ROP Per Run m/h	(Fph)
MEIT	7	2.2	13.0	(43.0)	6.0	(19.8)
DDPDM	5	5.4	21.6	(70.8)	4.0	(13.0)
BPDM	5	5.1	24.0	(78.8)	4.7	(15.4)
NPDM	10	3.5	17.1	(56.2)	4.9	(16.0)

*Typical directional run was set up with two joints of drill pipe, i.e., 18.3 m (60 ft).

Table 6

Typical MEI High Temperature TurboDrill Performance in EE-2
(Run 31, Table 2)

Date: Oct. 12-13, 1979
Depth: 3180 to 3217 m (10,433 to 10,552 ft)
Drilling Interval: ∿60 m (119 ft)
Approximate Formation Temperature: 310°C (500°F)
Shock Absorber: None
Bit: Smith Tool Co. Q9JL 31.1 cm. (12-1/4-in. diam)
Bit Load: <89 KN (20,000 lb_f)
Bent Sub: 1-1/2°
Flow Rate: 77 pump strokes/min ∿2252 ℓ/s (357 gpm)
Estimated Rotary Speed: 300-400 rpm
Inclination Angle Change Achieved: ∿1-1/2°
Total Rotating Time: >4.5 hours
Nominal penetration Rate: >7.9 m/h (26 ft/hr)
Condition of Bearing: no broken races, but estimated ≥1/2 h drilling life remaining

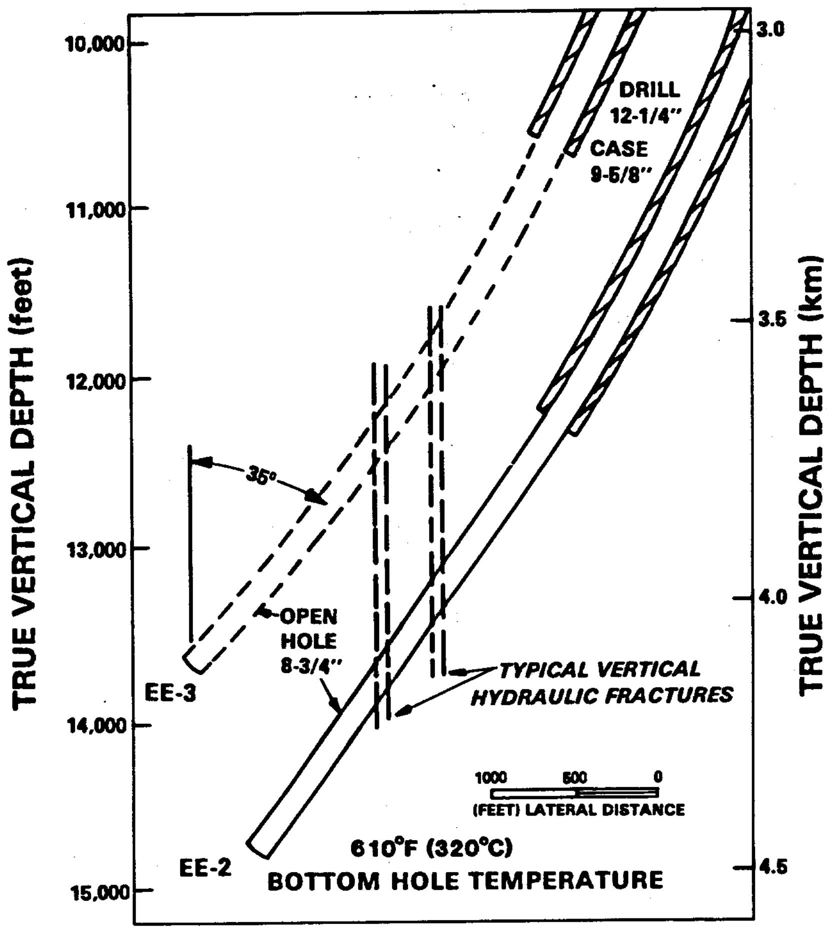

Figure 1. HDR Plan for Heat Extraction Reservoir.

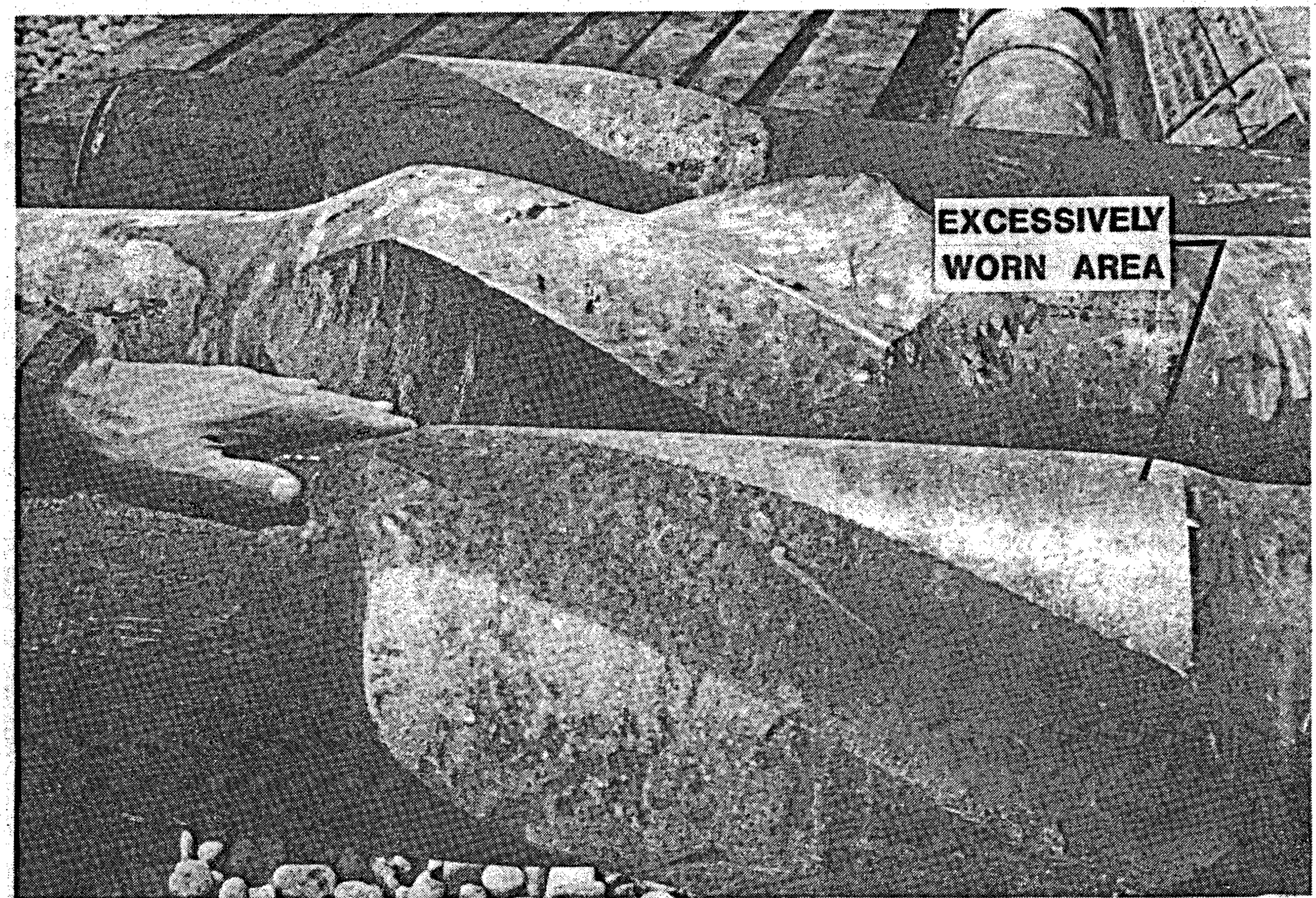

Figure 2. Severely Worn Blade Stabilizers.

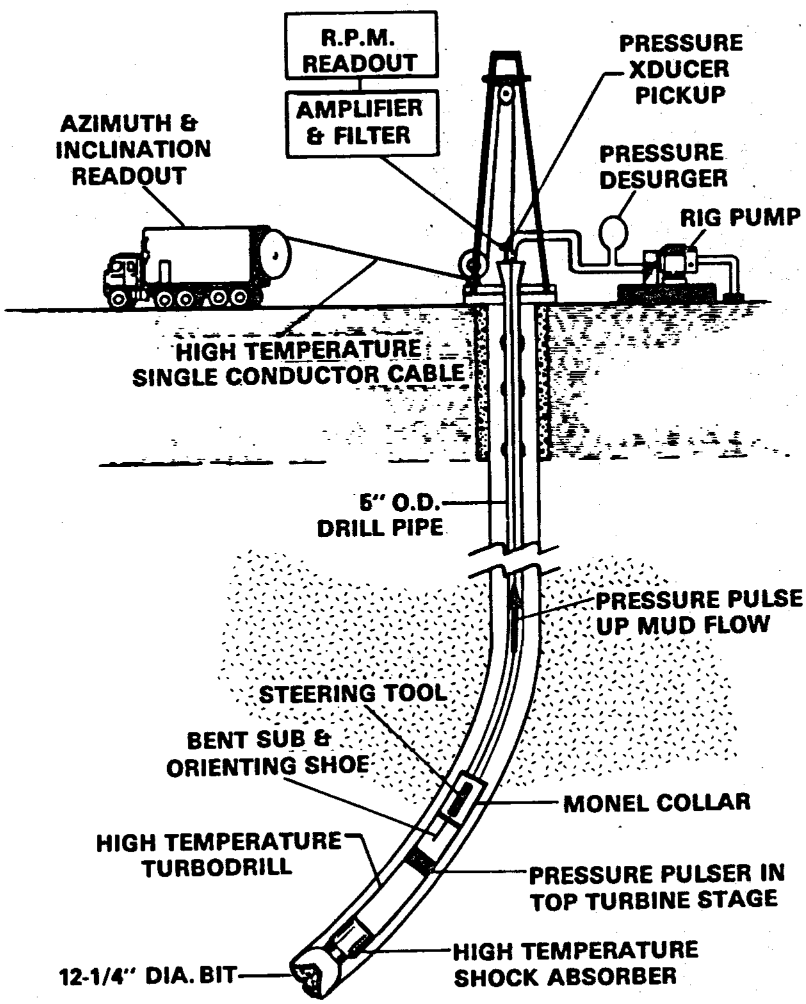

Figure 3. Directional Drilling System.

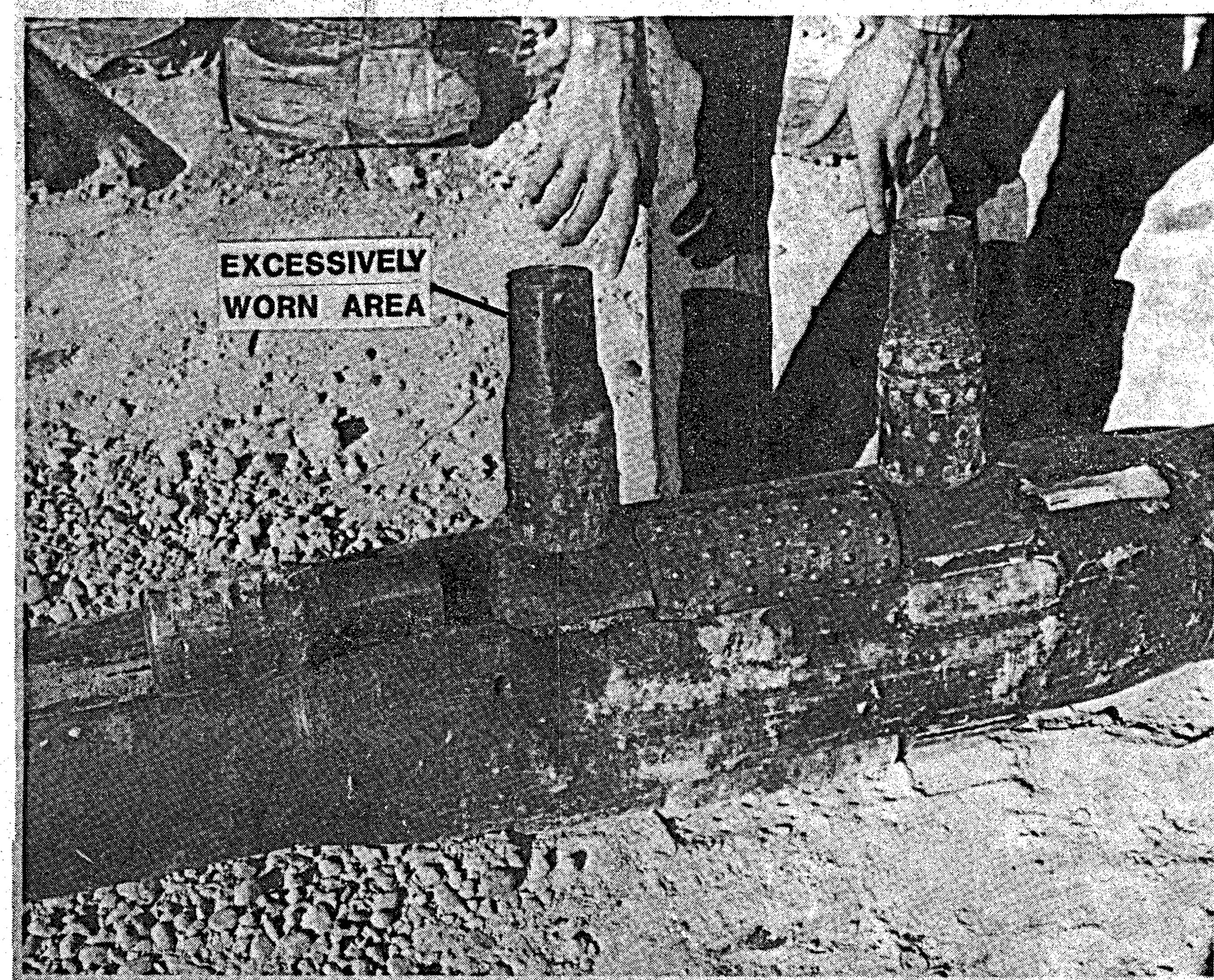

Figure 4. Severely Worn Reamer Rollers.

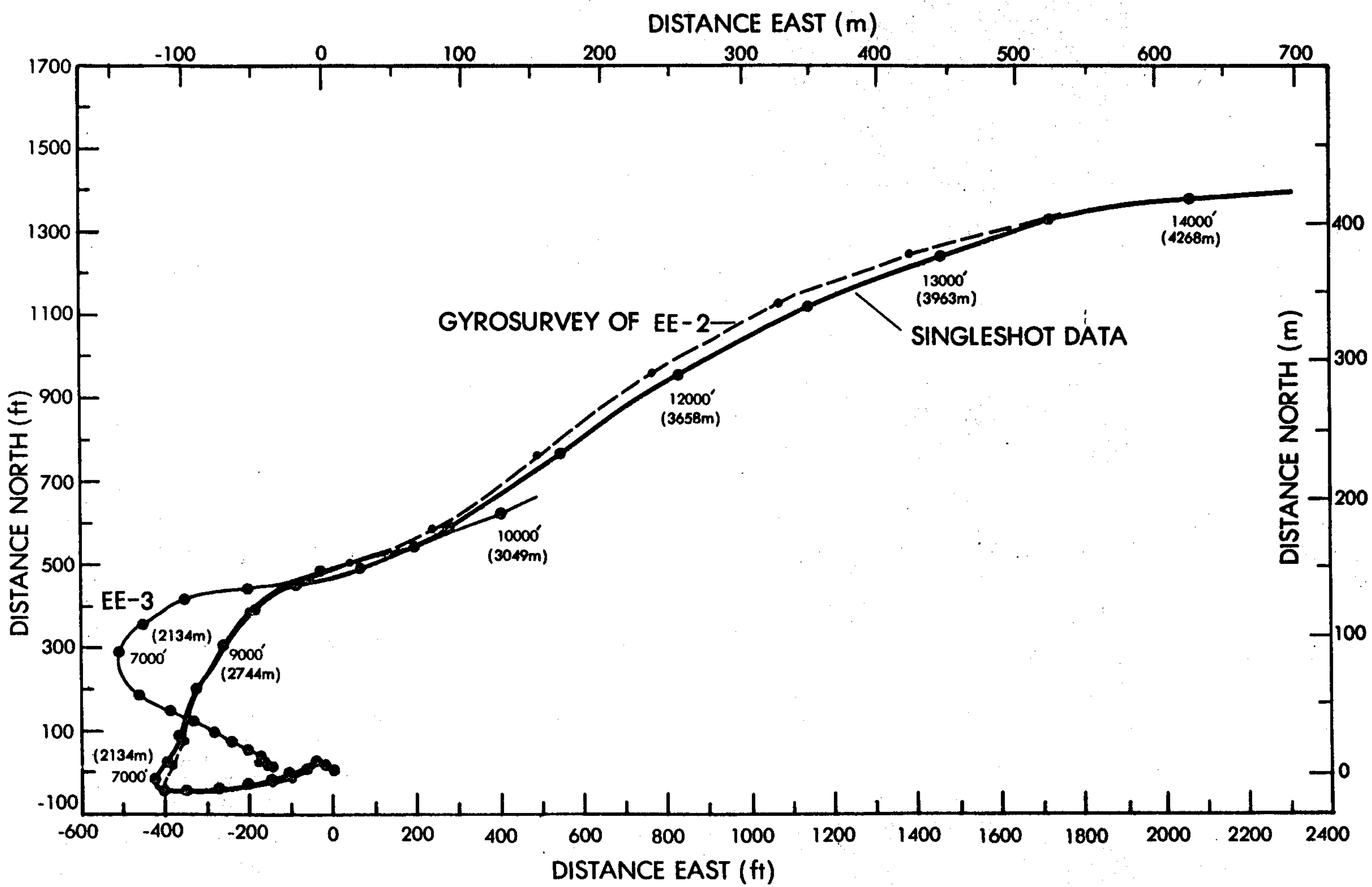

Figure 5. Plan View of EE-2 and EE-3.

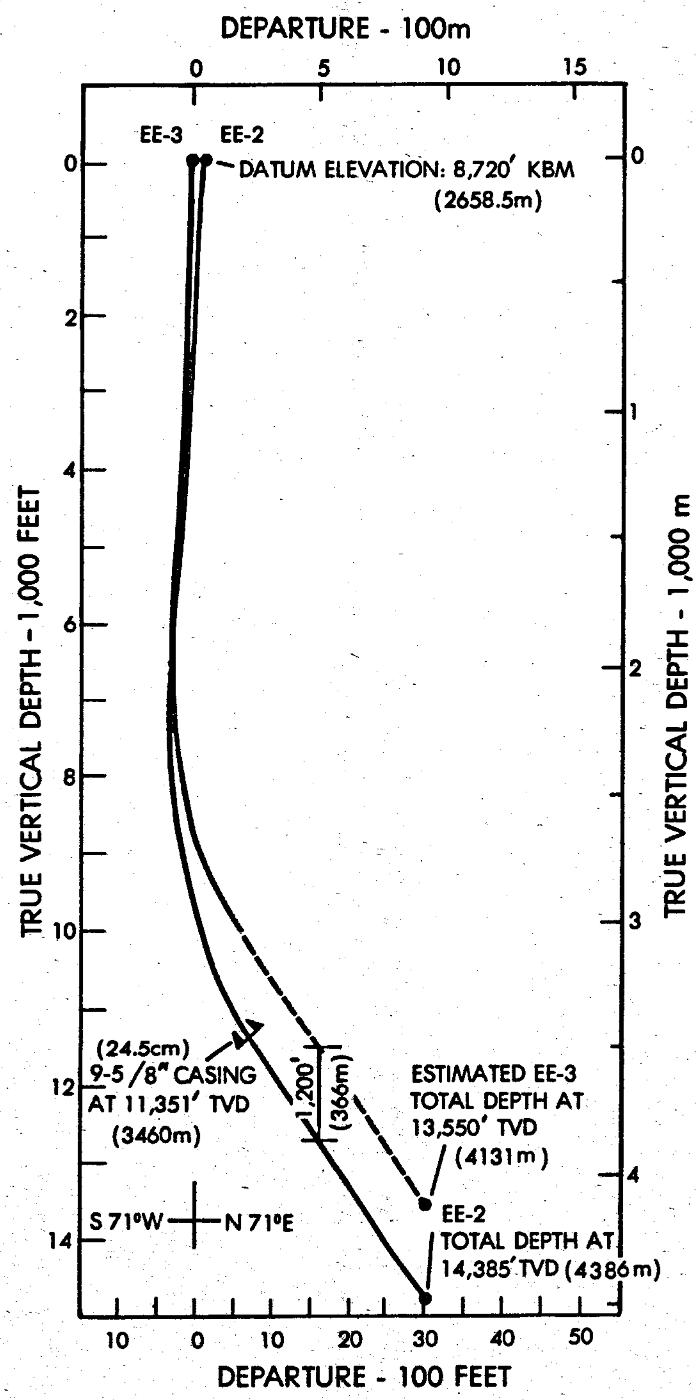

Figure 6. Section View of EE-2 and EE-3.