LA-UR -80-2086

66C

CONF-800931--3

TITLE: DIRECTIONAL DRILLING EQUIPMENT AND TECHNIQUES FOR DEEP HOT GRANITE WELLS

MASTER

AUTHOR(S): T. L. Brittenham, Grace, Sursen, Moore & Associates, J. W. Neudecker, J. C. Rowley, R. E. Williams

SUBMITTED TO: SPE to AIME: 55th Annual Fall Technical Conference and Exhibition of the SPE of AIME, Dallas, TX; September 21-24, 1980

University of California

LOS ALAMOS SCIENTIFIC LABORATORY
Post Office Box 1663 Los Alamos, New Mexico 87545
An Affirmative Action/Equal Opportunity Employer

Form No. 836 R3
St. No. 2629
12/78

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

DISCLAIMER

SPE

Society of Petroleum Engineers of AIME

This paper was presented at the 55th Annual Fall Technical Conference and Exhibition of the Society of Petroleum Engineers of AIME, held in Dallas, Texas, September 21-24, 1980.

ABSTRACT

Conventional directional drilling technology has been 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. Ambitious 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 a two-wellbore HDR system has resulted in the definition of operational limitations of many conventional directional drilling tools, instrumentation and techniques. The sucessful completion of the first wellbore, Energy Extraction Well No. 2 (EE-2), to a measured depth of 15,300 ft (4.7 km) in granite reservoir rock with a bottomhole temperature of 530°F (275°C) 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 8500 ft (2.6 km) of directional hole to a final inclination of 35° from the vertical at a controlled azimuthal orientation.

Carefully monitored performance of the directional systems used have indicated specific areas where additional equipment development is required. Additionally, sufficient data were collected to allow optimization of the drilling procedures and to improve the economics of application in future commercial developments of such alternate energy sources.

*This work was supported by the U.S. DOE, Division of Geothermal Energy.
References and illustrations at end of paper.

INTRODUCTION

Drilling Objectives

The HDR geothermal resource is derived from a subsurface region which exhibits a relatively high geothermal gradient. At the Fenton Hill site, granitic basement rock is encountered at a depth of 2400 ft (730 m) and exhibits a static geothermal temperature of 530°F (275°C) at a true vertical depth of 14,500 ft (4.48 km). Hydraulic fractures in the granitic rock are vertical and preferentially oriented in a northwesterly direction. The rock matrix is porous (<1%), but is essentially impermeable (1.0 to 10 microdarcies).

The method of heat extraction experiments currently underway at the Fenton Hill site require that two boreholes, one injection and one production well, be drilled to a depth exhibiting an economically attractive reservoir temperature. In order to enhance reservoir production objectives, the two wells will be inclined 35° from the vertical through the reservoir region at an azimuthal direction normal to the preferred fracture orientation. The wells will be drilled vertically coplanar with a constant separation of 1200 ft (370 m) between the underlying injection well and the overlying producer. Figure 1 illustrates the above described geometry of the EE-2/EE-3 extraction system in the 11,000 - 14,500 ft (3.35 - 4.48 km) reservoir region. The sequentially formed interconnecting fracture system will be hydraulically inflated and water circulated at a total flow rate of approximately 1500 gal/min (95 liter/sec).

Drilling Problems

The implications for drilling-related problems[1] during the construction of such a system are significant. The flow capacity requirements of the system require a minimum production hole drilled diam. of 8-3/4 in. (22.4 cm) and a minimum intermediate hole drilled diam. of 12-1/4 in. (31.4 cm).

The extremely hard and abrasive rock requires that all tricone bits have a tungsten carbide cutting structure. All drilling tools, bottomhole assembly components and the drillstring are subjected to severe abrasive wear that limits useful life.

Due to the impermeability of the rock matrix, no filter cake develops on the borehole walls which results in considerable axial and torsional drag on the drillstring. As a result, the use of high wall contact tools such as long strings of large diameter drill collars and fixed blade stabilizers is virtually prohibited. Also, the drillstring must be sufficiently strong to cope with this abnormally high frictional drag.

The required precision of borehole orientation and inclination requires that frequent magnetic surveys be conducted at temperatures to 530°F (275°C). Needed azimuthal corrections are performed with downhole drilling motor assemblies. Currently available high temperature motors require a wireline conveyed steering tool to insure proper orientation. Such tools also must be capable of reliable performance at elevated temperatures.

Many other drilling related tools and instrumentation are affected adversely as temperatures exceed 400°F (200°C). Reduction in yield strength of carbon steels, differential dimensional changes between components exhibiting dissimilar thermal expansion properties and the failure of elastomeric compounds are the most prevalent problems.

Solutions to Drilling Problems

Many of the directional drilling and related problems were solved by the application of conventional techniques using available equipment and instrumentation. As the rigorous demands placed on these tools and techniques increased however, it was necessary in most cases to make modifications. In some instances new tools and procedures were required.

The moderate temperature <400°F (200°C) portion of the EE-2 wellbore was drilled with available sealed friction and roller bearing bits with tungsten carbide cutting structures. Bit life was severely reduced in all cases due primarily to gauge wear. Considerable attention was given to obtaining minimum cost per foot performance by proper selection of bit type and drilling parameters. Magnetic and inclination surveying was performed with conventional single-shot tools with all data evaluated using the radius of curvature[2] calculation technique. Directional drilling using motor-driven assemblies was successfully accomplished through this interval utilizing positive displacement motors provided by Dyna-Drill (Division of Sii) and Baker Service Tools. Many conventional drillstring components such as drillpipe floats and mechanical drilling jars performed adequately during the drilling of this portion of the EE-2 well to a depth of approximately 10,000 ft (3.1 km).

However, several modifications were required to conventional directional drilling techniques and equipment, especially as drilling proceeded below 10,000 ft (3.1 km), temperatures exceeded 400°F (200°C) and borehole inclination approached 35° from the vertical. Motor-driven and rotary assemblies required the use of tungsten carbide insert bits appropriately modified to increase the life of the gauge cutting structure and protect the bit shirttail. The granite section in well EE-2 required that rotary-driven directional assemblies be stabilized with roller reamers versus the more commonly used fixed-blade stabilizers due to the significant torsional drag and excessive abrasive blade wear observed while drilling with the latter.

Directional surveying techniques and equipment also required modification to allow measurements to be performed at temperatures to 530°F (275°C). Wireline conveyed single shot, steering and multishot equipment had to be encased in heat shields and special techniques applied to obtain surveys. Multiconductor wireline used with the steering tools required high temperature rated materials to protect it from the invasion of wellbore fluids and insulation degradation.

As drilling progressed into the 35° slant portion of the hole it was necessary to further reduce the magnitude of axial and torsional drag between the drillstring and the borehole. Essentially all of the drill collar string was replaced with smaller outside diameter HEVI-WATE (Drilco Div. of Sii) drillpipe to reduce contact area. This reduced the drag substantially. After considerable pilot testing, a liquid lubricant was selected and successfully used to additionally reduce the magnitude of drillstring drag. Even with these remedial measures, it was necessary to replace a portion of the drillstring with high yield strength tubulars.

Several new equipment developments were required to complete the directional drilling operations. Foremost was the design and fabrication of a high temperature, all metal, turbine which was used for motor-driven corrections at borehole temperatures above 400°F (200°C). To optimize the operation of this turbine, a speed or RPM indicator was developed and operated. Additionally, high temperature shock absorbers were developed to reduce vibration and shock loads transmitted from the bit to the turbine to prolong the life of the motor bearings. Finally, a high temperature, axially responsive hydraulic drilling jar was developed and used during drilling and fishing operations. Although high temperature rated (500°F, 260°C) mechanical jars were readily available, the magnitude of downhole torsional drag made the manipulation of such tools virtually impossible.

DIRECTIONAL DRILLING APPLIED TO THE CONSTRUCTION OF HOT DRY ROCK SYSTEMS

HDR Geometrical Considerations

The construction of an HDR geothermal energy extraction system at Fenton Hill from a geometrical standpoint is rather straightforward. It requires that two slant-type wells be drilled to intersect the resource region with the two wellbores in the same vertical plane, a plane that is approximately normal to the fracture planes. In the case where the fractures are vertical, as at Fenton Hill, a limit is placed upon the angle of inclination by the maximum practical values from vertical that can be achieved with modern drilling technology. The length of the inclined or slant section of hole and the vertical separation of the two boreholes are based upon the fracture spacing, the power output and reservoir longevity required, and the wellbore spacing over which a high probability of fracture interconnection can be realized. The Fenton Hill system geometry is based upon a spacing of 10 - 15 vertical fractures having a horizontal separation of 120 - 180 ft (37 - 55 m).[3] A power output capacity of some 35 - 50 MW(t) with a reservoir drawdown of 20% in 10 producing years should be realized. Based upon results achieved in the currently operating shallower HDR system at Fenton Hill, a wellbore spacing of 1200 ft (370 m) will be attempted.

Direction Control

Of the several mechanical methods of altering the azimuthal course of a wellbore, the downhole motor coupled with a deflecting or bent subassembly, is the most positive and economic for application in the deep, hot granite boreholes drilled at Fenton Hill. Based upon the number of course alterations performed during the drilling of well EE-2 and the economics and mechanics of multiple whipstock settings, motor and bent subassembly is the only feasible alternative.

To insure that the motor and bent subassembly is properly oriented to provide the desired direction of deflection, a directional survey must be conducted. Depending upon the depth of operation, the torsional drag present and the degree of confidence in predicting the reactive torque of the drill motor, either a single-shot survey is performed with the motor static, or an electric line conveyed steering tool is used to provide a continuous measurement of tool orientation while the motor is drilling.

Once the desired course direction is attained, a rotary-driven assembly can be used to increase the magnitude of borehole inclination. A sequence of properly positioned wall contact tools (stabilizers) included in the bottomhole assembly just above the bit is used to provide lateral force at the bit, and results in an increase in borehole inclination. The rate of inclination build is dependent upon a multitude of variables that include borehole and tubular geometries, stabilizer placement, axial loading, etc.

Upon attaining the desired borehole inclination and azimuth orientation, a rotary-driven assembly with stabilizers is used to maintain the wellbore trajectory at its current attitude and direction. Natural drift of the well course, due to rock heterogeneities and drillstring-borehole interaction, may exceed tolerance levels and require additional directional corrections.

DESCRIPTION OF EQUIPMENT AND PROCEDURES

Motor-Driven System -- Equipment

Figure 2 illustrates the equipment and instrumentation used in the EE-2 motor-driven corrections of borehole azimuth. The two key elements of this directional drilling system are the downhole motor and the steering tool. The EE-2 directional drilling operations used three different types of motors and three separate steering tools, as presented in Table 1. The downhole turbodrill[4] was an equipment development project supported by the HDR program; all other tools are services available commercially. The fluid-driven motor provides drilling power without rotation of the drillpipe. This allows the desired orientation of the deflection subassembly to be preset and maintained as drilling proceeds. For application at Fenton Hill, the motor should be capable of high torque output and low rotational speed to enhance the performance of the roller bearing, tungsten carbide insert bits used in the granite. For use in the deeper, hotter portions of the wellbore, an all-metal tool rated substantially above 400°F (200°C), is necessary.

It was necessary to run a steering tool in all instances where the turbodrill was used. A dewar-type heat protection shield was required at the higher temperatures.

In order to realize any significant performance while drilling in the hard, abrasive granite with downhole motors it was necessary to use tricone, roller bearing, tungsten carbide insert bits. The majority of the runs was made either with an IADC code 835 bit or an improved geothermal bit. The geothermal bit featured a nonsealed roller bearing and a tungsten carbide insert cutting structure similar to the IADC 835 designation with high abrasion resistant inserts on the bit gauge.

A turbine tachometer[5] was developed to provide a surface indication of downhole motor speed. Operation of the unit was based upon a pressure pulse produced during each revolution of the turbine shaft by a perturbation in the blading of the motor. The pulse was transmitted through the fluid column in the drillstring to the surface where it was detected and processed. Nitrogen-operated pressure-pulse dampeners were assembled and placed in series in the mudline at the outlet of the triplex rig pumps. These dampeners were required to improve the performance of the turbodrill tachometer.

During initial laboratory drilling tests using the turbodrill it became apparent that a method of dampening the vibration and shock transmitted from the bit to the motor was necessary. Two high temperature rated shock absorber tools were constructed[1] based upon laboratory derived parameters.

A bent subassembly (1/2° to 2-1/2°) containing a muleshoe orienting sleeve was included in the assembly just above the motor. The function of this tool is to provide a directed side thrust to the bit that results from the intentional 1/2° to 2-1/2° misalignment of the axis of the rotary shouldered connections on either end of the subassembly. The plane of this misalignment is fixed with reference to the muleshoe assembly thus providing a method of relating tool face orientation to the measured azimuth.

A nonmagnetic drill collar (Monel) is included directly above the bent subassembly to eliminate magnetic disturbance to the steering tool magnetometer by the mass of steel contained in the assembly above and below the tool. A typical EE-2 drill motor assembly is shown in Table 2.

Motor-Driven System -- Procedure

The controlled change in azimuthal orientation of the wellbore direction is the more difficult drilling operation and requires continuous monitoring of the bottomhole assembly (BHA) orientation. This is necessary because variations in bit reactive torque are experienced by the drill motor as axial and subsequently lateral loading is applied, or as interactions at the bit-rock interface change. These variable reactive torques cause variable twist in the drillstring, result in alteration of tool orientation, and must be detected and compensated for. It is also important to monitor and restrict the sharpness of angular changes of the borehole (dogleg severity). Usual practice holds the total dogleg severity to less than 2° - 4° per 100 ft (30 m) of drilled hole. The azimuthal angle changes were performed with the typical BHA shown in Table 2. The general directional drilling procedure followed with the turbodrill was:

- Run drill motor assembly to bottom.
- Using rotary swivel, check motor rotation.
- Make up a 62 ft (19 m), two joint, length of drillpipe.
- Add the double joint stand to the drillstring and assemble the gooseneck head with a wireline pack-off.
- Run the steering tool to bottom and land it in the orienting (bent) subassembly.
- Rotate the drillstring to obtain the proper tool face orientation (allow for subsequent counterclockwise rotation of the assembly when motor is started and a reactive torque is applied).
- Start motor and drill ahead monitoring the BHA orientation and making corrections as necessary.
- After drilling down the two-joint stand of drillpipe, withdraw the steering tool and repeat the procedure as drilling conditions and angle changes indicate.

Rotary-Driven Build Assembly

Rotary-driven angle (or inclination) building assemblies were used to increase hole angle to 35° from vertical. After experimentation with increasingly strong build-up assemblies, satisfactory performance was finally derived from the multi-stabilizer/reamer assembly described in Table 2. Roller reamers were used as wall contact tools instead of the more common blade or pad type stabilizers due to the extreme torsional drag and rapid abrasive wear that occurred when drilling with the latter.

Operation of the buildup assemblies was primarily one of determining the proper weight on bit and rotary speed which provided the desired rate of inclination build, penetration rate and walk rate. Calculations were performed, and later verified operationally, to determine the maximum bit weight to be applied without creating a point of tangency between the first and second reamer. Considerable experimentation was also performed to define a relationship between rotary speed and the direction and rate of hole walk. Essentially no predictable relationship was determined, therefore the rotary speed for minimum cost per foot drilling was used.

Rotary-Driven Hold Assembly

Rotary-driven hold or lock-in assemblies were used to maintain a desired borehole inclination and azimuth orientation. Their primary application occurred in the vertical section of hole from the bottom of the 13-3/8 in. (34 cm) casing at 2463 ft (770 m) to the kick-off point (KOP) at approximately 7000 ft (2.2 km) and through the 35° slant portion of the hole from 11,600 ft (3.6 km) measured depth to total depth at 15,292 ft (4.7 km). A typical hold assembly is detailed in Table 2. Operation of the hold assembly was directed primarily at minimum cost per foot parameters.

Drillstring and Accessories

The 12-1/4 in. (31 cm) intermediate borehole from 2463 ft (770 m) to the angle built point of 11,600 ft (3.6 km) measured depth was drilled with a string of 8 in. (20 cm) OD drill collars until the torsional drag (measured at the surface) approached the make-up torque of the 5 in. (13 cm) OD NC50 connections on the drillpipe and the axial drag approached the tensile strength of the 5 in. (13 cm) OD drillpipe string (API premium used). At this point, essentially all drill collars were replaced with a string of 5 in. (13 cm) OD HEVI-WATE drillpipe. The same HEVI-WATE drillpipe string was used for bit loading for the drilling of the 8-3/4 in. (22 cm) slant portion of the hole; a 30% reduction in axial and torsional drag was realized.

In addition, to further reduce the magnitude of axial and torsional drag between the drillstring and the borehole, a procedure was developed to alleviate the problem with a lubricant added to the drilling fluid. A mixture of a modified triglyceride in alcohol (Baroid Div. of NL Ind., TORQ TRIM II) was added to the drilling fluid (water) at a concentration of 2.0 lb/bbl and the mixture was injected into the borehole in 50 bbl pills. A 50% reduction in drag was achieved.

As the torsional drag approached 5 - 10 revolutions of drillstring twist, the capability to successfully manipulate torsionally responsive mechanical drilling jars rapidly degraded. The mechanical jars were therefore replaced with a set of axially responsive hydraulic drilling jars (supplied by Houston Engineering Div., Wilson Industries), that incorporated several high temperature features which allowed their use for the remainder of the drilling operations.

In an effort to reduce the effect of abrasive wear of the drillstring by the granite borehole, a rigorous program of wear monitoring and repetitive application of sacrificial tungsten carbide hardfacing was instituted.

Directional Surveys

During rotary drilling operations single-shot directional surveys were conducted at regular intervals. At shallow depths and moderate temperatures, a conventional single-shot tool was run either on a 0.092 in. (0.23 cm) slickline or dropped in go-devil fashion prior to tripping the drillstring. As temperatures increased to above 250°F (121°C), however, it was necessary to utilize a smaller diameter single-shot tool inherently more heat resistant and encase it in a dewar-type heat shield. Additionally, as borehole inclination increased to 35° it was necessary to substitute a 5/8 in. (1.6 cm) braided wireline to effectively handle the increased drag on the wireline while retrieving the survey tool. At temperatures above 400°F (200°C), it was necessary to institute various operational techniques designed to cope with the elevated temperatures. For example, precautions were taken to exclude water vapor from both inside and outside the dewar flask.

DIRECTIONAL TECHNOLOGY APPLICATION

Well EE-2 was drilled from surface to an approximate kick off point (KOP) of 7000 ft (2.1 km) true vertical depth (TVD). Figure 3 is a plan view of the EE-2 wellbore projected into the horizontal plane. Wellbore deviation and directional walk maintained a stable trend of less than 2° at NWW until the well was unintentionally sidetracked in a SWW direction at a depth of about 2500 ft (770 m). Inclinaton subsequently increased to 4° to 9°, primarily due to the running of weak build assemblies.

A series of motor-driven deflection runs were performed below 7000 ft (2.1 km) to bring the wellbore course to a northeasterly direction. Following the successful azimuth alteration, attempts were made with various rotary-driven weak- and moderate-build assemblies to increase the wellbore deflection from vertical. These attempts were hampered by moderate-to-severe left walk tendencies which necessitated periodic motor-driven corrections to maintain a northeast well course. Utilizing strong rotary-driven build assemblies, the desired inclination of 34° from vertical was achieved at approximately 11,300 ft (3.48 km) TVD.

After reducing hole size, the EE-2 inclination was locked in at very near 34° inclination using strong to moderate packed hole assemblies, Table 2. The hole course exhibited slight-to-moderate left walk to 11,800 ft (3.63 km) TVD. Below this depth the walk tendency reversed to the right at a slight rate and continued to the final total TVD of 14,750 ft (4.48 km), or 15,292 ft (4.66 km) measured depth.

DIRECTIONAL SYSTEM RESULTS AND EVALUATION

The thirty motor-driven directional drilling runs used in the EE-2 well are tabulated in Table 3. Of the three different types of motors used, only one, the Maurer Turbodrill, demonstrated the capability to operate successfully above 400°F (200°C). Both of the positive displacement motors suffered thermal degradation of the stator. The turbodrill (run unsealed) however, did suffer considerable radial bearing wear caused by high lateral bit loads aggravated by the additional length of the shock absorber below the motor and by the use of bent subs greater than 1-1/2°. As evidenced in Table 4, all motors provided acceptable penetration rates. Downhole life was limited by severe bit gauge wear to only two to three operating hours however. Several instances of high dogleg severity and out-of-gauge hole created by a motor run required subsequent borehole reaming before drilling could proceed.

Of the three different types of steering tools used on EE-2, only one, the Scientific Drilling Controls steering tool (run without a heat shield) displayed the capability to perform reliably at temperatures above 400°F (200°C). Much of the steering tool failure however can be attributed to cable head and wireline problems. Motor runs which were performed without the shock absorber subjected the steering tools to intense vibration and shock resulting in extensive damage to tool components.

Both shock absorber tools developed for use below the downhole motor experienced seal failures as operating temperatures approached 380°F (193°C).

The pressure pulse turbine speed indicator performed satisfactorily to the maximum depth to which it was run, approximately 10,000 ft (3.1 km).

Tricone tungsten carbide insert bit performance while drilling with a downhole motor was predictable, although disappointing. Severe gauge wear at the higher rotational speeds (350 - 500 rpm) greatly restricted the useful life of motor-driven assemblies. For comparison, minimum cost per foot rotary drilling was obtained by operating IADC code 635 bits at high energy levels. Typical operating parameters of 5500 - 6500 lbs bit wt/in. of bit diameter, 65 - 75 rpm rotary speed and 4.5 - 5.5 hydraulic hp/in.^{2} of bit area resulted in penetration rates of 22 - 24 ft/h and maximum bit life of 30 - 40 h.

Roller reamers were used as wall contact tools for all stabilized assemblies after earlier attempts to use fixed blade and pad type stabilizers gave very poor wear performance. The reamers significantly reduced torsional drag and exhibited increased effective BHA life. Although the roller reamers provided less wall contact area than the stabilizers, satisfactory directional control was realized.

In consideration of the hostile environment to which it was exposed, drillstring performance was remarkably good. The most significant factor was the rapid abrasive wear of the drillstring. Although no downhole failures were attributed to this abnormal wear, some 4000 ft (1.2 km) of drillpipe had to be discarded or downgraded due to external wear. Repeated application of tungsten carbide hardbanding on the tool joints was used to retard the wear rate. Two downhole fatigue failures of the drillstring occurred. Both of these failures were attributed to fatigue crack growth from deeply penetrating, sharp, corrosion pits. This low incidence of fatigue failure in consideration of the length of directional hole and the magnitude of axial and torsional loading cycles applied to the drillstring, is due in part to the careful attention paid to the avoidance of high dogleg severity in the upper hole and to the use of low yield strength (75,000 psi) drillpipe for all but the upper 3500 ft of the string.

Performance of commercially available high temperature drillpipe floats was poor at temperatures above 350°F (177°C). The elastomeric seals became brittle and failed after only minutes of exposure. These failures resulted in several instances of plugged bit jet nozzles and downhole motors.

Figures 4 through 6 illustrate the performance of various rotary and motor-driven assemblies for changing or maintaining azimuth and inclination in the EE-2 granite borehole. The important points to be derived from these data are:

- Motor-driven bent subassemblies were an effective means of changing borehole azimuth.
- A very strong build assembly was required to obtain even a reasonable rate of inclination increase using rotary methods.
- Moderate packed hole assemblies were effective at maintaining inclination.
- Higher buildup rates were realized as inclination from vertical increased.
- Walk rate was difficult to control while using rotary-driven angle building assemblies.
- The effect of azimuth orientation on the buildup rate in well EE-2 was minor.
- The tendency of the EE-2 borehole to walk or change azimuth is reduced at higher inclinations for both buildup and hold assemblies.
- The direction and rate of walk appears to be a function of both depth and azimuth orientation.

Although the above observations are for a single well at this point, they are data which will be used during the planning and drilling of subsequent wells at the Fenton Hill Site.

CONCLUSIONS

1. Conventional directional drilling motors, wireline steering tools, shock absorbers, bits, stabilizers, surveying tools, drilling jars, drillpipe floats and many other associated equipment items are not directly applicable to such hostile downhole environments in deep wells at the Fenton Hill site.

2. Equipment capable of successful performance in such a drilling environment has been developed and tested.

3. Additional directional drilling sytem developments are required to increase operational efficiency and reduce costs of HDR drilling.

4. Considerable "state-of-the-art" knowledge has been developed concerning directional drilling planning, equipment and procedures in hot, hard abrasive rock.

ACKNOWLEDGMENT AND DISCLAIMER

The authors wish to thank the many firms and individuals that supported the EE-2 directional drilling operations with their equipment, instruments, services, and expertise. However, reference to a company, product name, service, tool or equipment item does not imply approval or recommendation of the product, service, or tool by the University of California (LASL) or the U.S. Department of Energy to the exclusion of others that may be suitable.

REFERENCES

1. Williams, R. E., Rowley, J. C., Neudecker, J. W., and Brittenham, T. L.: "Equipment for Drilling and Fracturing Hot Granite Wells," SPE Paper No. 8268, presented at the SPE 54th Annual Technical Conference and Exhibit, Las Vegas, NV, September 23-26, 1979.

2. Wilson, G. J.: "An Improved Method for Computing Directional Surveys," Transactions, AIME, 243, 871-876 (1968).

3. Cummings, R. G., et al.: "Mining Earth's Heat: Hot Dry Rock Geothermal Energy," Technology Review, Vol. 81, No. 4 (February 1979) 2-19.

4. Maurer, W. C., Nixon, J. D., Matson, L. W., and Rowley, J. C., "New Turbodrill for Geothermal Drilling," 12th Intersociety Energy Conversion Engineering Conference Proceedings, Washington, DC, Vol. 1, pp. 204-211 (1977).

5. McDonald, W. J., et al.: "Development of Turbodrill Tachometer," Geothermal Resources Council Transactions, Vol. 4 (September 1980).

TABLE 1 DRILL MOTORS AND STEERING TOOL SERVICES USED IN EE-2 DIRECTIONAL DRILLING

DRILL MOTOR

Type	Diam. In.	Temperature Rating	Supplier	Key
Positive Displacement	6-3/4	≈175°C (350°F)[a]	Baker Service Tools (Houston, TX)	BPDM
Positive Displacement	7-3/4	≈155°C (310°F)[a]	Dyna-Drill Smith International (Irvine, CA)	DDPDM
Turbine	7-3/4	≈275°C (530°F)	Maurer Eng., Inc. (Houston, TX)	MEIT

STEERING TOOL

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.

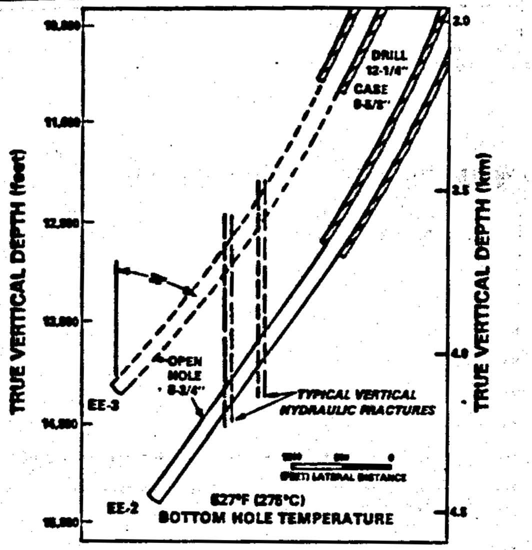

Fig. 1 - HDR Drilling Plan for EE-2/EE-3 Heat Extraction Reservoir.

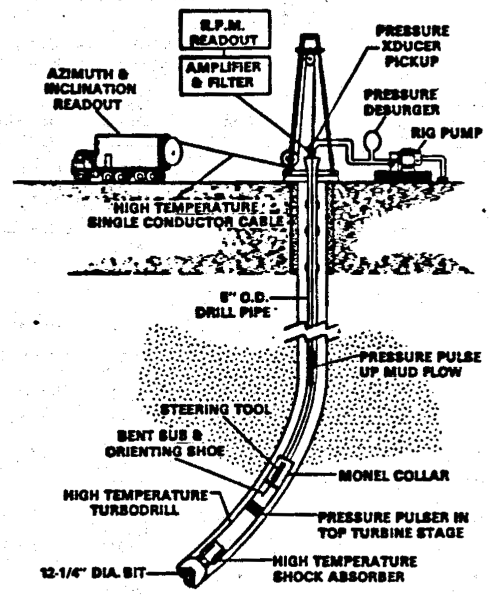

Fig. 2 - Directional Drilling System.

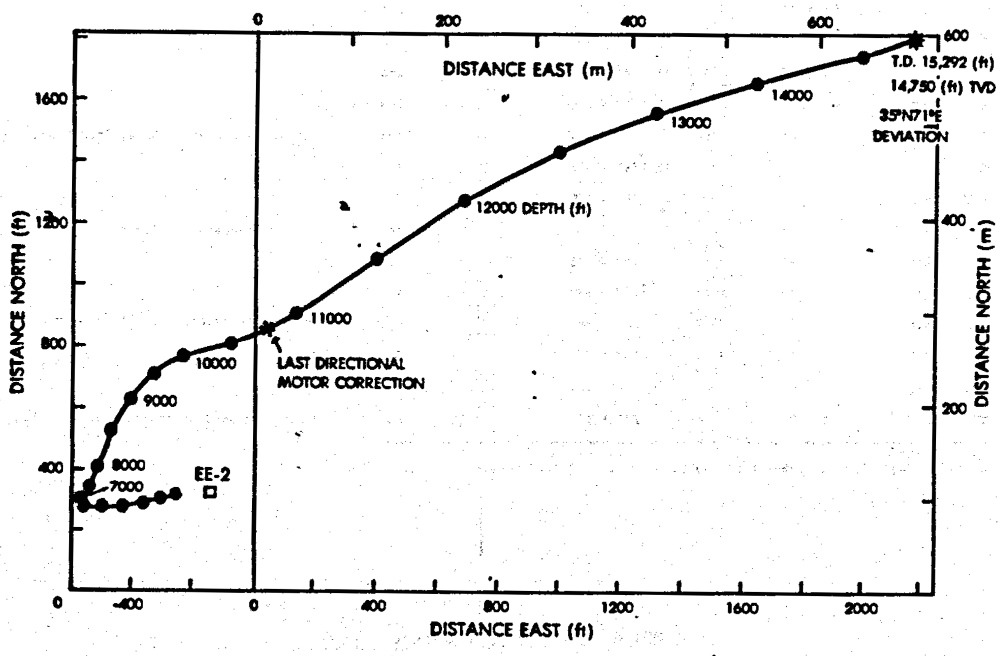

Fig. 3 - Plan View of EE-2 Well, Based on Single-Shot Data.

TABLE 2

TYPICAL BOTTOMHOLE ASSEMBLIES FOR DIRECTIONAL DRILLING IN HDR WELL EE-2

BHA for Drill Motor Azimuthal Angle Alteration	BHA for Rotary Inclination Angle Increase	BHA for Rotary Inclination Maintenance
12-1/4 in. diam bit Shock absorber Drill motor Crossover sub	12-1/4 in. diam bit 3-Point BH reamer Crossover sub 6-3/4 in. diam monel drill collar	8-3/4 in. diam bit 6-Point BH reamer 6-3/4 in. diam short drill collar 3-Point string reamer
Bent-orienting sub	6-3/4 in. diam short drill collar	6-3/4 in. diam monel drill collar
8 in. diam monel collar	6-3/4 in. diam drill collar	3-Point string reamer
12 8 in. diam drill collars 21 Joints HWDP*	Crossover sub 3-Point string reamer 8 in. diam drill collar Crossover sub 10 8 in. diam drill collars 8 Joints HWDP* Drilling jars 13 Joints HWDP*	4 6-3/4 in. diam drill collars 20 Joints HWDP* Drilling jars 13 Joints HWDP*

*HEVI-WATE drill pipe.

Table 3. Summary of azimuthal directional drilling runs for well EE-2
(Note: All runs with 12 1/4" dia. bits)

Directional Drill Motor Run No.	Drill Motor*	Steering Tool Service*	Bent Sub Angle	Measured Depth, meters (feet)[a]	Borehole Deviation**	Distance Drilled, (feet)	Shock Absorber[b]	Remarks
1	MEIT	N.A.	-0-	1497 (4912)	5 3/4°,S64°W	17 (57)	Yes	First field trial of 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°,----	8.0 (26)	No	DOT tool damaged
4	DDPDM	—	2°?	2017 (6597)	3°,----	24 (79)	No	
5	DDPDM	—	2°?	2011 (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	
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 8300'-9303' with DOT 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°	2753 (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, Sperry Sun 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	3.0 (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 BPDM
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

*See Key Table 1. **See Fig. 3.
[a]Depth at end of run [b]Refer to Williams et al, 1979, Ref. 1. [c]HADES version

TABLE 4

MOTOR ASSEMBLY PERFORMANCE SUMMARY

Motor Type	Number of Runs	Average Hours per Run	Average Footage per Run	Average ROP per Run (Fph)
MEIT	21	2.8	59.8	21.6
DDPDM	6	4.5	54.7	12.3
BPDM	4	7.8	48.8	6.2

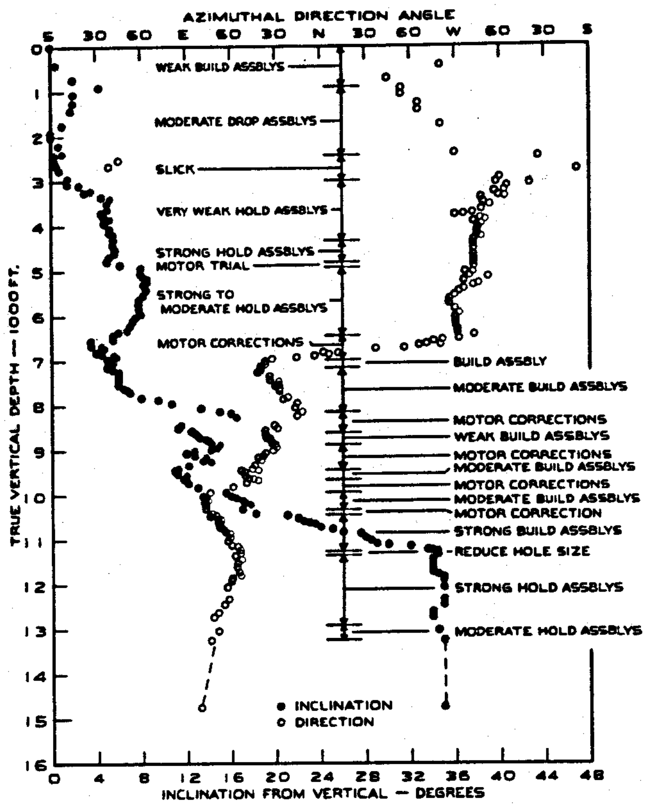

Fig. 4 - EE-2 Inclination and Direction vs. Depth.

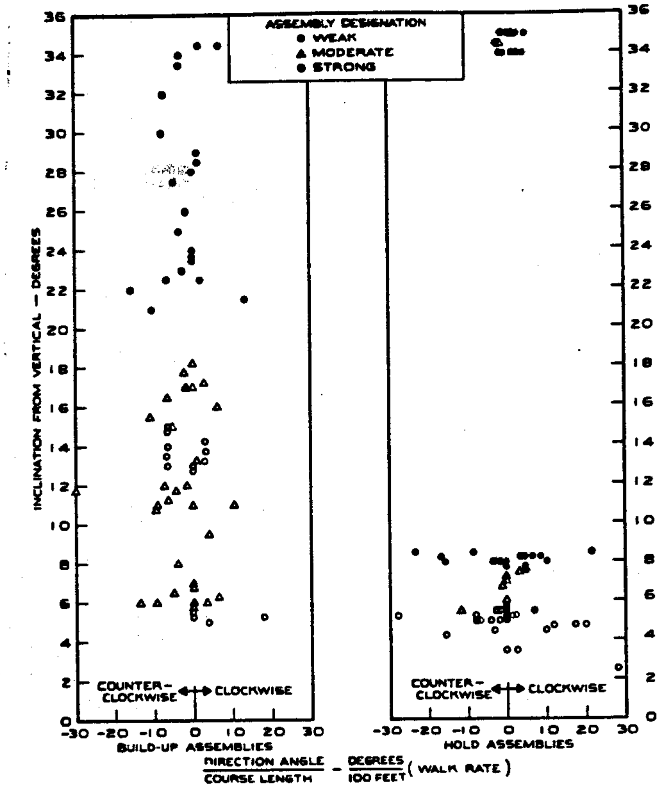

Fig. 6 - Walk Rate vs. Inclination, Influence of BHA.

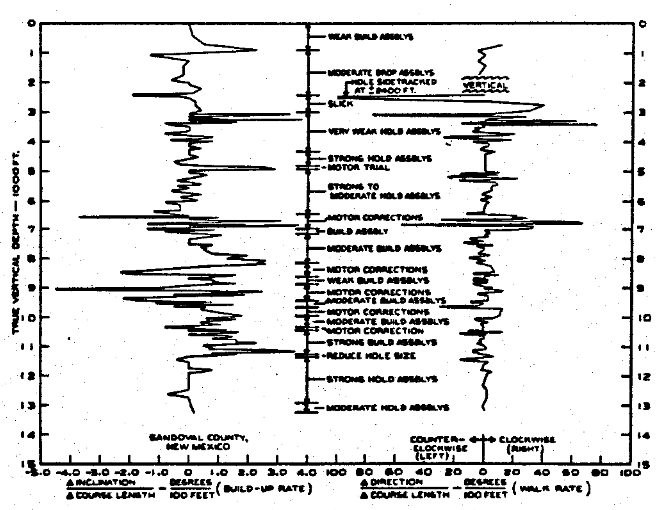

Fig. 5 - Build-up Rate and Walk Rate vs. Depth.