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AUTHORS: W. C. Maurer, Maurer Engineering, Inc.
J. D. Nixon, Maurer Engineering, Inc.
L. W. Matson, Maurer Engineering, Inc.
J. C. Rowley, LASL

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los alamos scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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NEW TURBODRILL FOR GEOTHERMAL DRILLING*

W. C. Maurer, J. D. Nixon and L. W. Matson
Maurer Engineering, Inc., Houston, TX 77018

J. C. Rowley, Los Alamos Scientific Laboratory, Los Alamos, NM 87545

Abstract

Maurer Engineering, Inc., is developing a new high-temperature, 275°C (550°F), turbodrill for use in drilling geothermal wells. Performance of existing downhole drilling motors is limited in these holes because the motors contain materials, often elastomers, which degrade rapidly at elevated temperatures. Materials for the advanced turbodrill were selected for high-temperature service conditions. The advanced turbodrill will be tested in the Los Alamos Scientific Laboratory's hot dry rock geothermal wells. The turbodrill is designed so that some of the drilling fluid is diverted through the axial thrust roller bearings for lubrication and cooling. Design of the turbine blading provides four times the torque of existing drill motors. The design also incorporates spare seals which are activated as the primary components wear, thereby minimizing time and expense of round trips for repairs or replacement. The torque-rotational characteristics were selected to be compatible with tungsten carbide button insert bits for long-life operation and efficient penetration in hot, hard geothermal formations. Drill motors have been used in drilling and completing wells in several geothermal fields. They have been especially valuable in directional drilling. The new temperature-resistant turbodrill is intended to provide increased effectiveness in all directional drilling applications and offer economic alternatives for completing geothermal wells.

NOMENCLATURE

b	:	Turbodrill rotor vane width, m (ft)
g_c	:	Gravitational constant, 1 Kg·m/(N.S^2) (32.2 ft/sec^2)
n	:	Number of turbine stages
P	:	Turbodrill power, W (hp)
Δp	:	Drill motor pressure drop, Pa, (psi)
Q	:	Mud pump flow rate, m^3/s (ft^3/s)
q	:	Drill motor volumetric displacement per revolution, m^3 (ft^3/rev)
S	:	Rotational speed of turbodrill, s^{-1}(rpm)
S_R	:	Rotational speed at runaway, s^{-1}(rpm)
T	:	Drill motor torque, N·m (ft·lb$_f$)
T_o	:	Torque at stall conditions, N·m (ft·lb$_f$)
w	:	Fluid density, Kg/m^3 (lbm/ft^3)
β	:	Exit angle of turbine blade, rad (degree)
λ	:	Turbodrill fluid contraction coefficient
ε	:	Turbodrill fluid loss coefficient
η	:	Overall drill motor efficiency
η_m	:	Mechanical efficiency of turbodrill
η_v	:	Positive displacement motor volumetric efficiency .

INTRODUCTION

Functions and Uses of Drill Motors. The basic purpose of downhole drill motors is to provide the power needed to rotate the drill bit at the bottom of the borehole. This replaces the usual transmission of power through the drill string rotation from the surface. Drill motors have proven especially advantageous for (a) situations where drill pipe wear, and fatigue, and twist-off are likely to occur, e.g., excessively crooked holes; and (b) drilling of deviated wells when direction and trajectory control are important to achieve a preselected target in the producing reservoir.

Drill motors were first tested in the 1920's, but did not find widespread use until the 1950's , when turbodrill use began in the Soviet Union[1,2]. By the early 1960's, about 85% of the Soviet's oil and gas wells were being drilled with turbodrills. This usage has decreased to perhaps 70% because rotary drills are now being used in most Soviet wells deeper than 4 km (12,500 ft) because of increased trip times required to replace worn turbodrills.

Drill motors are widely used in the United States for drilling directional holes, but not for straight hole drilling because of bearing and seal life problems. Current rotating seal designs typically limit bit pressure drop to only 700 to 2100 kPa (100 to 300 psi), which is not adequate for a good bottomhole cleaning of cuttings. Commercial downhole motors operate at speeds of 5 to 16 s^{-1} (300 to 1000 rpm), whereas roller cone drill bits operate most effectively at 1 to 3 s^{-1} (50 to 150 rpm). At higher motor speeds, the bit bearings tend to fail in 5 to 15 hours, whereas at lower speeds they last up to 200 hours. High speeds also cause failure of the motor bearings in 20 to 40 hours, which is not adequate for economic straight hole drilling. Improved drill motors which will: 1) operate at speeds of 2 to 4 s^{-1}

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

(100 to 200 rpm), 2) allow bit pressure drops of 7000 to 14050 kPa (1000 to 2000 psi), and 3) have bearing life in excess of 200 hours would find widespread use in deep wells, in the straight hole portions of offshore oil and gas wells, and for directional drilling.

Use of downhole motors for geothermal wells has generally followed the practice of oil and gas well drilling. They have found their most extensive geothermal applications for directional drilling. In the development of geothermal fields with complex volcanic geology, rugged terrain, or environmental constraints, it is economical to drill several wells from a common location, or several bottomhole completions from a single straight well, both involving directional drilling. The drill motors used for geothermal drilling are subject to the limitations indicated, but are also subjected to the high temperatures of geothermal wells, which further reduces the service life of bearings and seals and restricts the use of elastomeric materials.

A review of the various types of downhole motors, i.e., turbines[3,4], positive displacement[5,6], and electric drills[7,8], indicated that a turbodrill would be the most practical to upgrade for high-temperature service because of the relative temperature insensitivity and simplicity of the all-metal turbine blading. The problems of bearings and seals are essentially common to all downhole drill motor systems, and the proposed solutions to these problems will be applicable to all downhole drill motor developments.

Geothermal Applications. It has been reported that no directionally drilled completions have been attempted in the high-temperature geothermal fields under development in eastern Europe, Iceland[9], Latin America, India, and Indonesia. The United Nations has indicated[9] that no directional drilling has been done in connection with UN-associated drilling and geothermal development. Soviet geothermal drilling has not been reported in detail [9], but it is likely that turbodrills have been utilized in the geothermal drilling program in the Soviet Union since that is their principal mode of drilling. Japan[10] has utilized directional drilling with turbodrills to provide deviated well completions to accommodate for difficult terrain and institutional or environmental constraints in the extensions of their Hachimantai field. Review of the land forms of Japan's identified geothermal areas and their plans[11] for operating nearly 200 drill rigs per year, indicates that directional drilling of multiple wells from a single location will continue there. The Philippine geothermal development by Union Oil of California has also indicated [12] a program of multiple wells from individual locations.

Directional drilling with downhole motors has been used to control oil and gas well blow-outs. In this case an off-set intersect well is drilled for the purpose of shut off and plugging. This approach has also been used to control geothermal well blowouts in the extensively developed Lardarello, Italy [13] and Wairakei, New Zealand[14] fields.

Directional drilling has been utilized in the development of The Geysers, CA geothermal field, primarily by using the DynaDrill (Smith International, Inc.)[5] positive displacement drill motor, Fig. 1. The primary objective of using directional drilling at The Geysers is to drill multiple wells from a single pad. One drilling contractor[15] indicated that about 15 wells have been successfully completed at The Geysers by that technique. It was also indicated that several essentially vertical wells have been provided with multiple side-tracked completions in the fractured reservoir rock at The Geysers. The ERDA-funded Raft River, ID geothermal project[16], conducted by the Idaho National Engineering Laboratory, has effectively utilized a downhole motor for directional drilling of multiple bottoms for the third well in the project. This three-legged completion has enhanced the productivity of the well by factors of from three to five. The effectiveness of this approach in fracture-controlled formations, where a 20% to 30% increase in well cost produced a significant increase in productivity, will undoubtedly be more widely applied in future geothermal drilling programs for reservoirs of this type.

The initial experimental approach to a hot dry rock geothermal project[17], funded by ERDA and conducted by the Los Alamos Scientific Laboratory (LASL), is based on the concept shown in Fig. 2. The first borehole drilled into hot 200-300°C (400-600°F) rock was hydraulically fractured and the second well was then directionally drilled to intersect the fracture[18].

Directional drilling in hard, hot granite has proven to be slow and expensive, but possible. Several approaches have been taken to improve the situation. The DynaDrill Div. of Sii has provided an experimental unit, Fig. 3, with a coolant flow hole in the rotor. This modification should provide better cooling by the drilling fluid and enhance the life of this drill motor at ∿200°C

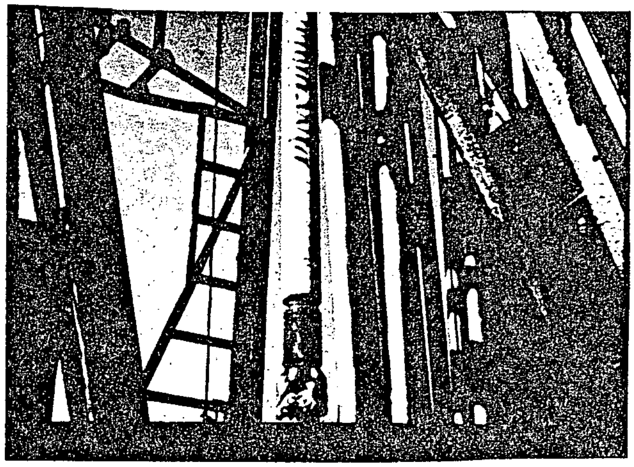


Figure 1. Positive Displacement (Moineau) Drill Motor Used in Majority of Directional Drilling of Geothermal Wells (courtesty Dyna-Drill Div., Smith International, Inc.).

(400°F). For higher temperature service, the design of the turbodrill discussed in this report was initiated.

Other Energy Resource Applications. Directional drilling has been widely utilized in oil and gas production, Fig. 4. Downhole drill motors for directional drilling are also projected to find increasing use in other energy resource areas, such as: in-situ coal gasification[19], methane drainage of coal seams, Fig. 5, and producing tight gas sands[20], Fig. 6.

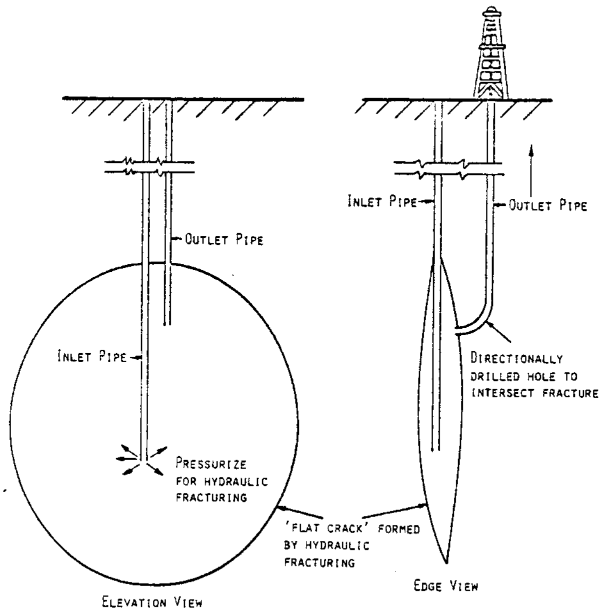


Figure 2. Concept of Creating a Hydraulic Fracture Geothermal Energy Reservoir in Hot Dry Rock.

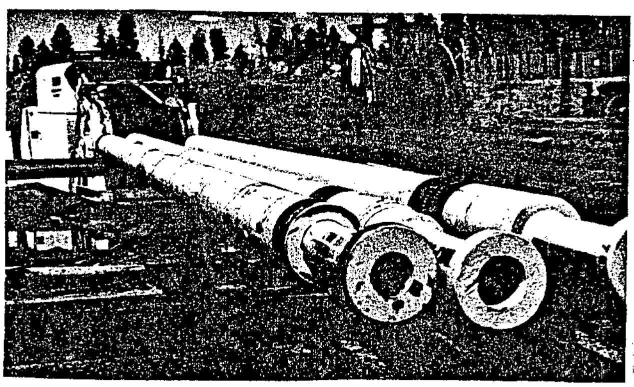


Figure 3. Special Dyna-Drills, Provided with Coolant Flow Hole in Rotor.

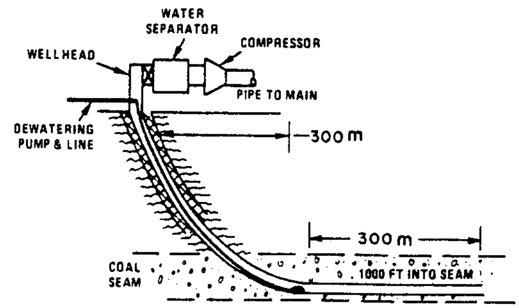


Figure 5. Methane Drainage of Coal Seams.

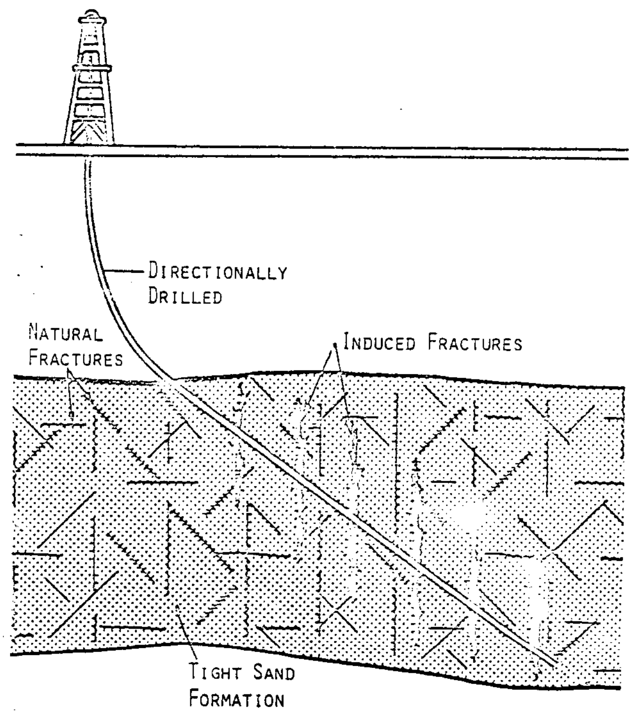


Figure 6. Natural Gas from Tight Sands.

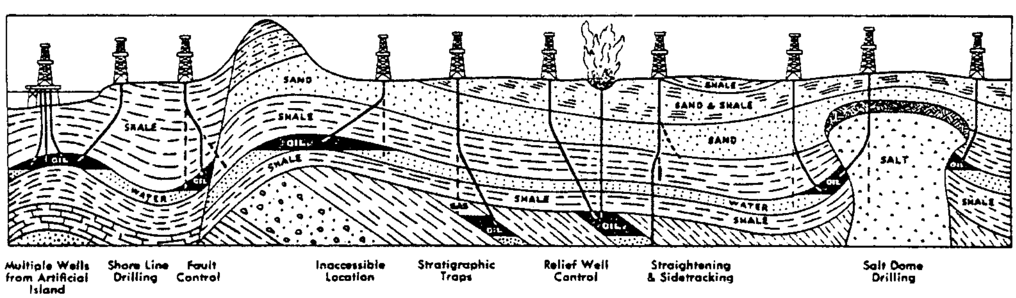


Figure 4. Illustrations of Directional Drilling in Oil and Gas Wells.

HYDRAULIC POWERED DRILL MOTORS*

There are two basic types of downhole hydraulic powered drill motors: positive-displacement and turbines. Positive displacement motors have the distinct operational advantage that the rotary speed is directly proportional to the pump flow rate,

$$S = \eta_v (Q/q),\ s^{-1}(\text{rpm}) \quad (1)$$

where the motor volumetric efficiency η_v varies from 0.7 to 0.9. The flow rate is therefore a direct measure of the rotary speed of the motor. Volumetric efficiency is less than unity and decreases as motor torque increases because of the increased pressure drop across the motor increases the leakage.

The torque delivered by a positive displacement motor is directly proportional to the pressure drop, ΔP, across the motor,

$$T=2.12\times10^{3}\eta\Delta p(Q/S),\text{N}\cdot\text{m}(T=3.07\eta\Delta p(Q/S),\text{ft.lb}_f). \quad (2)$$

The rig mud pressure gauge can therefore be used to monitor the bit torque.

Four types of positive displacement motor concepts (Moineau, vane, piston, and gear) have been proposed for drill motors; but of these, only the Moineau type has been used for geothermal drilling. The currently available** units are manufactured by Dyna-Drill, Fig. 7. The Dyna-Drill is powered by an eccentric steel shaft rotating in a rubber stator.

Rotation occurs as fluid is forced under pressure into the cavities between the rotor and the stator. A connecting rod containing universal joints converts eccentric rotation of the rotor to concentric motion of the drive shaft, which rotates the drill bit. Dyna-Drill motors are limited to maximum operating temperatures of about 177°C (350°F), primarily by the rubber stator. Attempts to increase the temperature capabilities using higher temperature elastomers have been of limited success because of their unfavorable fabrication properties and high costs.

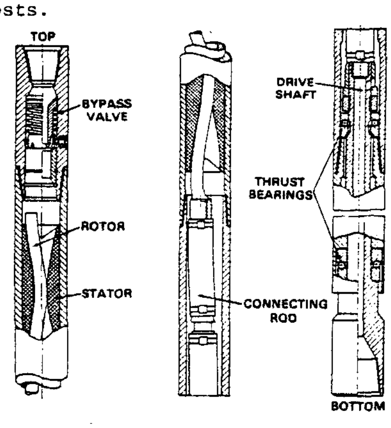


Figure 7. Moineau Motor Concept (Dyna-Drill).

*These are usually termed "mud motors" in the drilling industry.
**Several other firms are working on drill motor versions of the Moineau concept.

Turbodrills utilize axial flow turbine blades to apply torque to the drill bit, Fig. 8. The torque developed by a turbodrill is maximum when the turbodrill stalls. This stall torque[21],

$$T_o=\eta_m\frac{nw\,(1-\varepsilon)Q^2}{\lambda\pi b}\tan\beta,\text{N}\cdot\text{m}\left(T_o=\eta_m\frac{nw(1-\varepsilon)Q^2}{g\lambda\pi b}\tan\beta,\text{ft.lb}_f\right). \quad (3)$$

Equation 3 shows that the turbine torque can be increased by increasing the number of turbine stages, the fluid flow rate, or by increasing the exit angle of the turbine blades.

The torque delivered by the turbodrill decreases as the rotary speed increases according to:

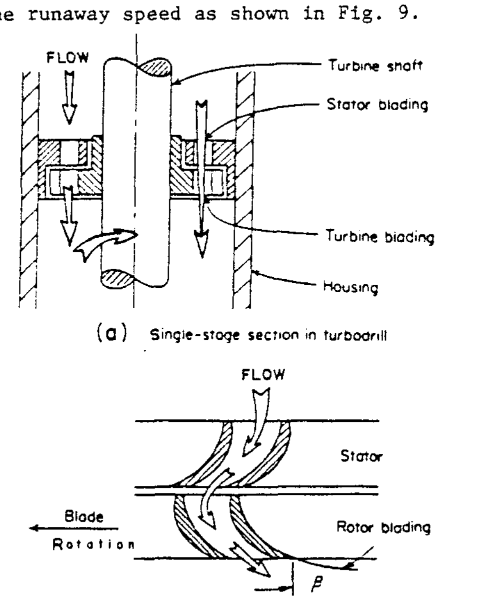
$$T = T_o(1-S/S_R),\ \text{N}\cdot\text{m}\ (\text{ft.lb}_f) \quad (4)$$

where S_R is the runaway speed. Thus the torque decreases from a maximum at stall conditions to zero at runaway speed.

The turbodrill power output equals:

$$P = 2\pi ST,\text{W}\ \left(P = \frac{2\pi ST}{33000},\text{hp}\right) \quad (5)$$

The turbodrill delivers maximum power output at 50% of the runaway speed as shown in Fig. 9.



(a) Single-stage section in turbodrill

(b) Typical cross section of turbine blading showing the flow of fluid through one stage of the unit

Figure 8. Turbodrill Blading.

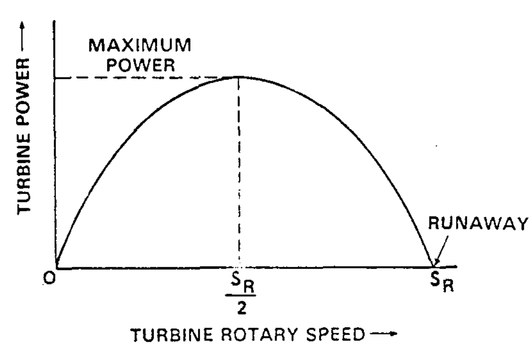


Figure 9. Typical Turbodrill Power Curve.

The runaway speed of a typical oilfield turbodrill, Fig. 10, ranges from 13 to 33 s^{-1} (800 to 2000 rpm) so these turbodrills deliver maximum power output at speeds of 6 to 16 s^{-1} (400 to 1000 rpm). Because this high rotary speed results in short bearing life in roller bits, diamond bits are usually used. The high operating speeds of Dyna-Drills 5 to 10 s^{-1} (300 to 500 rpm), also result in short bit bearing life.

One problem with turbodrills is that the speed of the turbine is not directly related to the flow rate and is therefore unknown in most cases. Current turbodrills utilize 80 to 160 turbine stages to provide power to the bit. Existing turbodrills are often limited to maximum operating temperatures of about 177°C (350°F) due to the use of elastomeric thrust and radial bearings, and the seal designs which are widely used. Turbodrills are usually not operated at no-load conditions because doing so produces "chattering" and rapid failure of bearings. The need to balance the hydraulic and bit forces limits the force that can be applied to bits to about 110 kN (25,000 lb), whereas many bits drill most effectively at bit forces of 180 to 270 kN (40,000 to 60,000 lb). This reduced bit force greatly reduces drilling rate, especially in the hard rocks encountered in many geothermal wells. Motors with higher thrust bearing capabilities are needed to drill these hard rocks. Another serious limitation of Dyna-Drills and available turbodrills is that they do not deliver sufficient torque for optimum use of tricone drill bits. Consequently, the bits have to be operated at further reduced bit forces which further reduce drilling rates. Another limitation of existing drill motors is that the bits must be operated with reduced bit hydraulics due to inadequate seals, and the mud jets on the bits are therefore inefficient in removing the broken rock from the bottom of the hole.

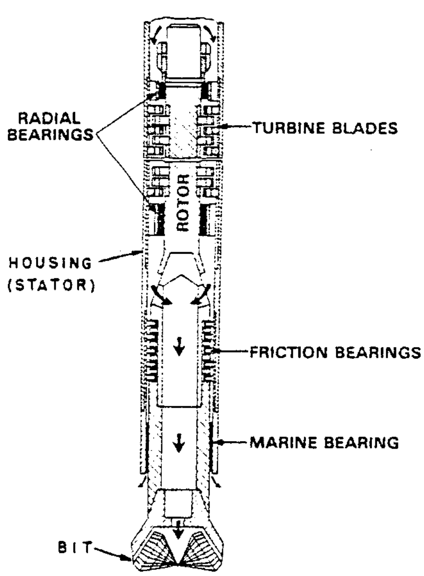


Figure 10. Typical Turbodrill.

ADVANCED GEOTHERMAL TURBODRILL DESIGN AND DEVELOPMENT

Due to the temperature limitations of existing downhole motors, two advanced turbodrills are being designed for use in higher temperature wells. These turbodrills utilize advanced turbine blading which results in shorter length, more powerful motors. These turbodrills are also designed to overcome the major limitations of current units as outlined above. Two types of turbodrills are under development:

- Directional Turbodrill - This turbodrill contains no elastomers and is designed to operate in hot geothermal wells at temperatures up to 350°C (660°F). The drilling fluid is water and the motor contains a flow-through bearing pack.
- Straight Hole Turbodrill - This turbodrill contains a sealed lubrication system in which the bearings operate in lubricant and which excludes the abrasive drilling mud. The unit is applicable to oil field drilling in addition to geothermal wells.

The design specifications for these two turbodrills are given below.

GEOTHERMAL TURBORDRILLS - SUMMARY SPECIFICATIONS

Parameter	Directional	Straight Hole
Rotary Speed:		
With Roller Bits -	1.6-3.25 s^{-1} (100-200 rpm)	Same
With Diamond Bits -	6.7-13.3 s^{-1} (400-800 rpm)	Same
Diameter:	197 mm (7-3/4 in)	Same
Length:	6.4 m (21 ft)	7.6 m (25 ft)
Power Output:		
At 2.5 s^{-1} (150 rpm) -	26.8 kW (36 hp)	48.6 kW (65 hp)
At 13.3 s^{-1} (800 rpm) -	91.5 kW (123 hp)	165 kW (222 hp)
Flow Rate:	0.19 m^3/s (400 gal/min)	Same
Temperature Limitations: (Static without damage)	350°C (660°F)	Same
Bearing Life:	50 h at 275°C (525°F)	100-200 h at 150°C (300°F)

Directional Turbodrill. The high temperature turbodrill, Fig. 11, allows a portion of the drilling fluid to flow through the roller bearings to cool and lubricate them. A controlled constriction at the bottom of the unit provides for about 10% of

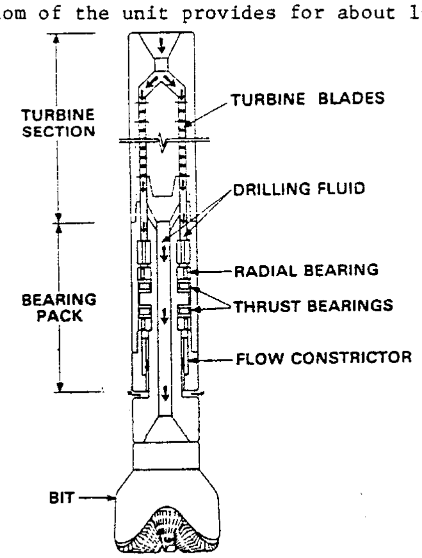


Figure 11. New Directional Turbodrill for Geothermal Wells.

the drilling fluid to be diverted through the bearings with the remaining fluid flowing through the bit nozzles.

The directional and straight hole turbodrills utilize an advanced turbine blade design which will deliver 4 to 5 times more torque per stage than the blading used in existing turbodrills. Higher torque is achieved by an improved blade configuration which effectively increases tanβ (see Eq. 3). This allows the new turbodrills to be shorter in length and to deliver 100% more power than existing motors of comparable diameter. By applying higher bit forces, these turbodrills can be operated at rotary speeds of 1.6 to 3.2 s^{-1} (100 to 200 rpm) with high torque and bit loads required for carbide button bits. With diamond bits and lower bit forces they can be operated at speeds of 6.7 to 13.3 s^{-1} (400 to 800 rpm).

The bearing pack design uses roller thrust bearings as shown in Fig. 12. Conventional motors utilize either rubber friction bearings with a temperature limitation of about 130°C(260°F) or ball bearings made from steels which have draw temperatures of about 230°C (450°F). When these bearings are operated above this draw temperature, they lose their heat treat and soften, resulting in more rapid failure. The bearings used in these new geothermal turbodrills are made from M50 tool steel which has a draw temperature of 600°C (1100°F) thereby overcoming one serious limitation. The selected roller bearings have much higher thrust capability than applicable ball bearings because the load is distributed along a line instead of at a point. The roller bearing selected has a load rating of 550 kN (122,000 lb_f), compared to 147 kN (33,100 lb_f) for the ball bearing. The high load rating of these thrust bearings will allow the application of the 180 to 360 kN (40,000 to 80,000 lb_f) bit forces needed for fast drilling with 200 to 310 mm (7-7/8 to 12-1/4 in) roller bits. The load rating of a bearing is usefully defined as the bearing load at which 10% of the bearings will fail after 1 million revolutions. The standard calculation for bearing life at 8.3 s^{-1} (500 rpm) at the above loads indicates that the predicted life of the roller bearing is 80 times greater than that of the ball bearing. Although it is unlikely that the roller bearings will last the predicted 3580 hours, because of the high dynamic bit loads present, it is likely that they will last the required 100 to 200 hours. Because of the high cost of operating geothermal drilling rigs ($3000 to 5000 per day), it is desirable to replace the bearings after 100 to 200 hours to prevent costly downhole failures and round trips to replace the motors or fish out broken components. For easy field maintenance the bearings are therefore placed in a separate bearing assembly that is easily removed from the turbine section.

Roller radial bearings (Fig. 13) are also to be utilized to accommodate lateral loads on the drive shaft produced by tool deflections in crooked holes, asymmetrical bit loads, or other factors. In general, radial bearing failures are not as great a problem as thrust bearing failures because space constraints on the radial bearings are not as great as those on the thrust bearings. If necessary, additional radial bearings can be easily added, whereas additional thrust bearings require means for distributing the thrust loads across the bearings.

Straight Hole Turbodrill. The straight hole turbodrill, Fig. 14, is designed to operate in abrasive drilling mud. The bearings are sealed in lubricant which is pressurized by mud acting on top of a floating piston. Improved high pressure rotary seals allow the use of high bit nozzle pressure drops, which results in a faster drilling rate. Pressure drops of 2100 to 5600 kPa (300 to 800 psi) are possible across diamond bits and 3500 to 7000 kPa (500 to 1000 psi) across roller bits, as compared to only 1400 to 3500 kPa (200 to 500 psi) with existing motors. These higher pressure drops are made possible by the new graphite seals which rapidly dissipate heat from the sealing surfaces.

Although this turbodrill is currently designed for moderate temperature drilling, it is suited for drilling the shallower portions of geothermal

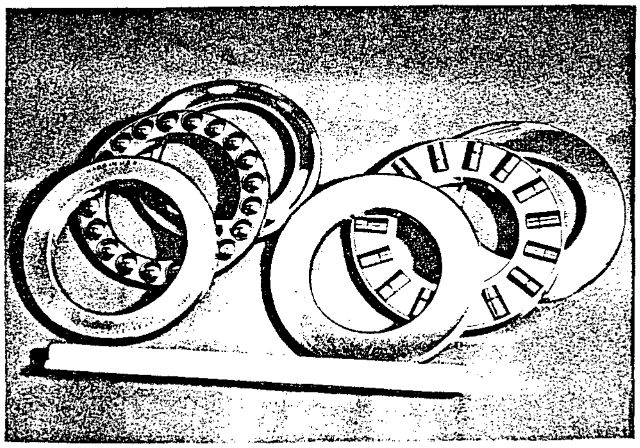


Figure 12. Ball and Roller Thrust Bearings.

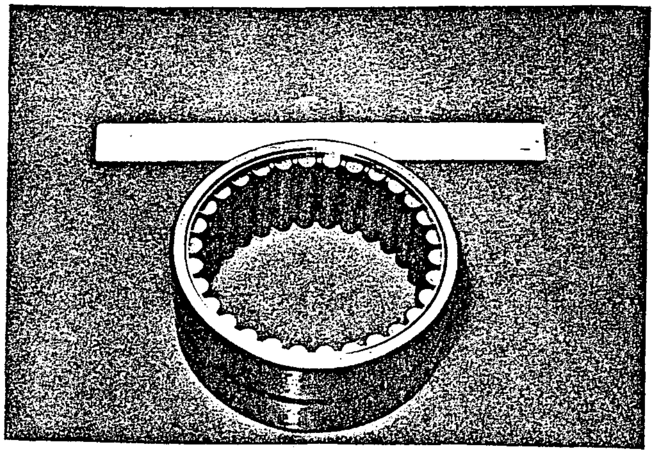


Figure 13. Radial Bearing.

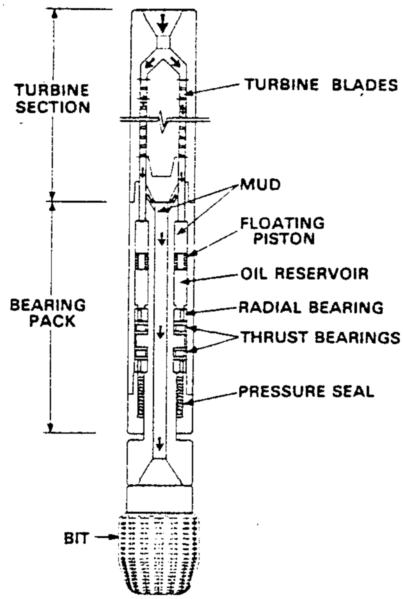


Figure 14. Straight Hole Turbodrill.

wells, where drilling muds are required to prevent lost circulation into porous or fractured formations. The temperature gradient in geothermal wells varies with hole depth; consequently, only the bottom portions of most geothermal wells are hot enough to necessitate the use of the extreme temperature turbodrill. When drilling with abrasive drilling mud, the straight hole turbodrill is preferred and should be used as long as possible before switching to the geothermal turbodrill.

Special high temperature metal seals and high temperature lubricants can be used in the straight hole turbodrill to extend the temperature capabilities of this tool from 150 to 200°C. With these seals and lubricant, this sealed turbodrill is capable of drilling to considerable depths in most geothermal wells. Where geothermal wells are drilled with water, the geothermal turbodrill is preferred since the water cools the bearings and is not abrasive.

CONCLUSIONS

Drill motors have found rather widespread application in the directional drilling of geothermal wells. These drilling practices have thus far been derived from oil and gas field experience and hardware. An advanced high temperature turbodrill could provide an economic advantage for geothermal development by providing additional drilling of several wells from a single location. The design of such high temperature turbodrills has been accomplished, and their major features and advantages are presented in this paper. The motivation for development of the advanced turbodrill was the directional drilling requirements in hot, hard granite for the LASL hot dry rock geothermal project. However, additional applications to other energy resource development projects can be expected.

ACKNOWLEDGEMENTS

Many individuals in the drilling and geothermal energy development industries contributed to our survey of the present usage of drill motors and indicated present equipment limitations and needed improvements. The authors wish to thank J. W. Neudecker, LASL, for his numerous contributions to the turbodrill design effort. The continuing support, interest and encouragement of C. Carwile, ERDA, Division of Geothermal Energy, is appreciated.

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