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High-Temperature Directional-Drilling Turbodrill

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CONTENTS

HIGH-TEMPERATURE DIRECTIONAL-DRILLING TURBODRILL

by

J. W. Neudecker and J. C. Rowley

ABSTRACT

This report summarizes the development of a high-temperature turbodrill for directional drilling of geothermal wells in hard formations. The turbodrill may be used for straight-hole drilling but was especially designed for directional drilling. The turbodrill was tested on a dynamometer stand, evaluated in laboratory drilling into ambient temperature granite blocks, and used in the field to directionally drill a 12-1/4-in.-diam geothermal well in hot 200°C (400°F) granite at depths to 10 500 ft.

I. INTRODUCTION

The Los Alamos National Laboratory, Hot Dry Rock (HDR) geothermal project concept[1,2] requires directional drilling in hot granite at formation temperatures to 300°C (600°F) and depths to 15 000 ft. When the turbodrill project was initiated (1975), existing downhole motors used for oil and gas well directional drilling were not designed to withstand the high temperatures encountered in geothermal wells. Consequently, a high-temperature turbodrill was developed as a joint effort by the Laboratory and Maurer Engineering, Inc. (MEI), Houston, Texas.

A schematic diagram of a directional drilling system[3,4] is presented in Fig. 1. In addition to the turbodrill, several other elements are depicted: (1) a bent sub to provide side (lateral) load on the bit, (2) a steering tool or guidance wireline instrument (usually a magnetometer and inclinometer

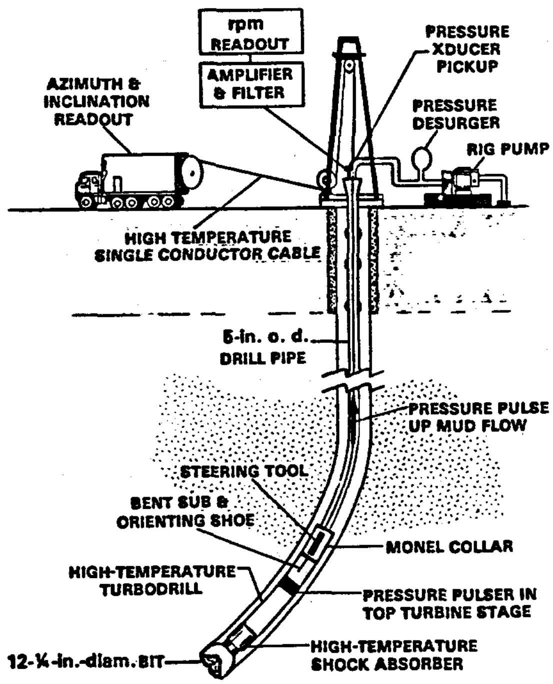

Fig. 1.
Directional drilling system for geothermal wells.

combination) used to set up and monitor the desired direction of drilling, (3) a rotational speed indicator (pressure pulser), (4) fluid flow from the rig mud pumps, and (5) a shock absorber subassembly to protect the turbodrill bearings from the shock and vibration loads as a result of rough drilling in hard crystalline reservoir rock at Fenton Hill, New Mexico.

II. DESIGN FEATURES AND GOALS

Design objectives of the high-temperature turbodrill developed by MEI were the target performance characteristics listed in Table I.

These performance goals were selected to meet the HDR project directional drilling requirements and were partially derived from laboratory data for rotary drilling with 12-1/4-in.- and 9-5/8-in.-diam bits in granite blocks. Thus, the general objective was to match the turbodrill performance as closely as possible to the bit drilling requirements of granite. Of special importance were (1) the relatively low drilling rotational speed needed to yield a

TABLE I

TURBODRILL TARGET PERFORMANCE CHARACTERISTICS

Temperature Rating:	To drill in hot, 275°C (530°F) very hard (granite) rock. The turbodrill shall withstand this temperature for extended periods of time during drilling operations and withstand a soak at 300°C (600°F) for a few (12) hours with no fluid flow.
Drill Speed:	100 rpm nominal with a 50-200 rpm range.
Bit Weight:	35 000 lb_f with a 20 000-50 000 lb_f range.
Penetration Rate:	In hard granite; >10 ft/h.
Bit Size and Type:	Both 12-1/4-in. and 9-7/8-in. hard rock, carbide button bits.
Torque:	Capability sufficient to turn both bit sizes at above rpm.
Flow Capacity:	~400 gpm.
Bit Power on Bottom:	~25 hp minimum.
Maximum Bent Sub Angle:	<3°.
Downhole Makeup:	6-5/8-in. standard API threads (box) on both ends; used with 8-in.-diam collars.
Circulating Fluid:	Water.
Total Length of Motor:	<30 ft.
Useful Drilling Depths:	~6 km.
o.d. of Housing:	7-3/4-in. maximum.
Vibration Protection:	Shock absorber may be used.

reasonable life for the three-cone carbide insert bits to be used, (2) a short length for downhole eccentric offset with the bent sub, (3) high torque to match bit requirements and high-lateral bit loads generated because of directional drilling forces, and (4) temperature tolerance up to ~300°C.

The design features and considerations that were required to meet these target performance characteristics are listed below.

- Turbine blades should provide maximum torque in the shortest possible length. This would require an efficient turbine blade design and would give desired directional control in highly deviated boreholes.
- Low rpm characteristic, provided for enhanced bit life, must be a design tradeoff with drill motor operating stability.
- Materials for both turbine blades and structural elements (housing, shafts, etc.) were chosen for high-temperature performance, that is, strength and differential expansions/contractions.
- Roller bearings were selected to give enhanced bearing life because of reduced contact forces as compared to ball bearings.
- Because clear water was to be used as the drilling fluid,[3] it was possible to consider operation of the bearings unsealed, that is, to flow a percentage (up to ~10%) of the water through the bearings for cooling and "lubrication." This approach avoided the problems of the (then) unavailability of high-temperature seals. (The configuration of the seal-bearing section of the turbodrills used would allow retrofit of suitable high-temperature seals when they became available.)
- Steel alloy, heat treatment, and stress concentration factor (geometric stress risers) selections were dictated by the high-soak temperature requirement, hot aqueous operating environment, and the severe shock/vibration stresses expected that would create a potential for fatigue failures.

The 7-3/4-in.-diam directional turbodrill developed in this project is shown in detail in the assembly manuals (Appendix A) and parts list (Appendix B).

III. LABORATORY TESTS

The as-built performance characteristics of the 7-3/4-in.-diam turbodrill were measured on a dynamometer test stand at the MEI test facilities and also while drilling into granite test specimens at the Drilling Research Laboratory (DRL), Salt Lake City, Utah.

A sketch of the MEI dynamometer test stand is shown in Fig. 2, and Fig. 3 is a photograph of the test facility. Figure 4a shows turbodrill torque vs rotary speed as measured in the MEI facility.

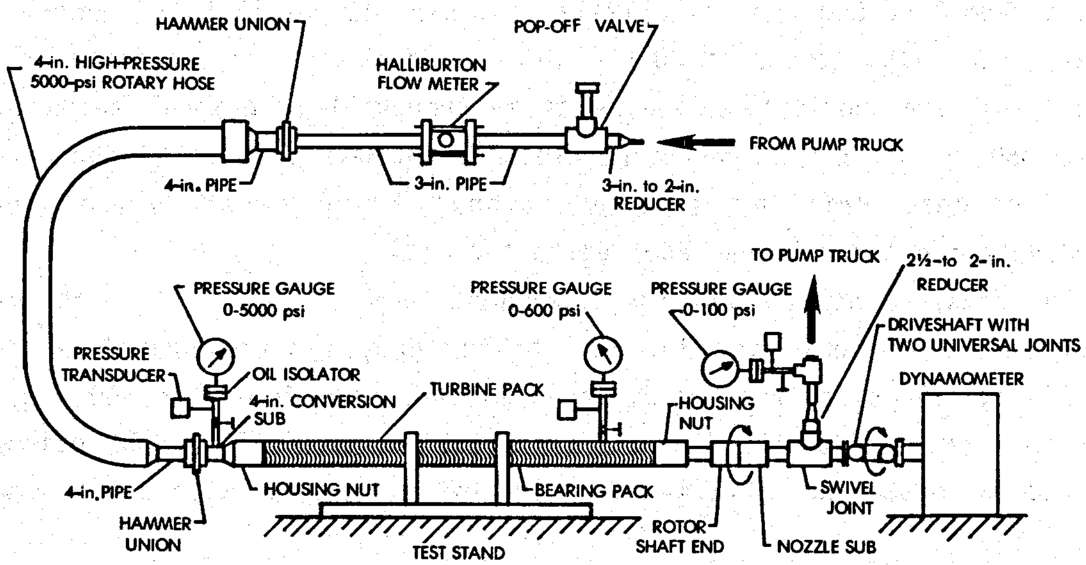

Fig. 2.
Dynamometer test facility schematic.

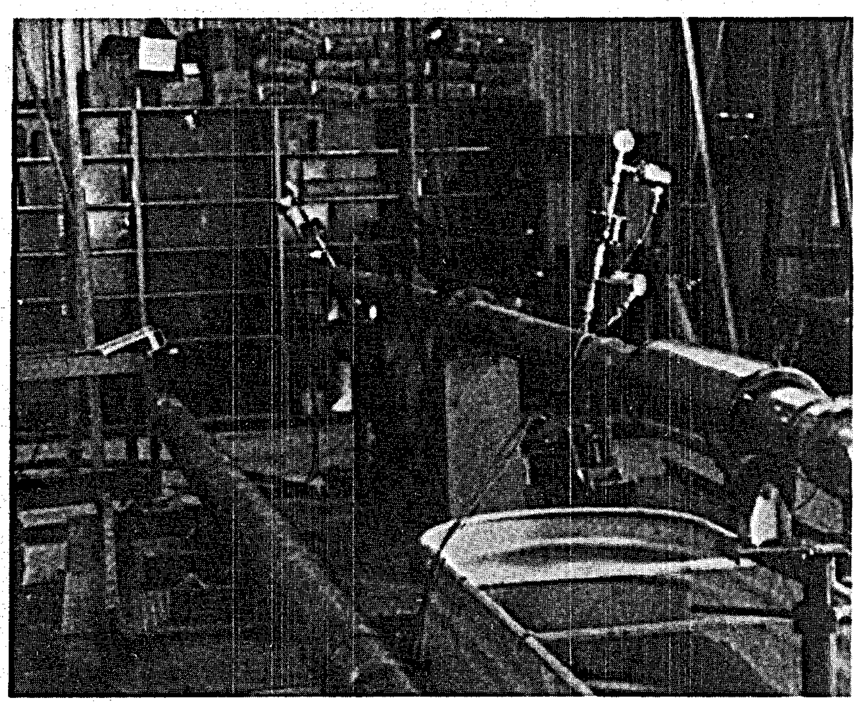

Fig. 3.
Photograph of MEI dynamometer test facility.

The torque output of the turbodrill decreases linearly with increased rotary speed as shown in Fig. 4a. At a flow rate of 400 gpm, the turbodrill output torque decreases from 1100 to 540 ft-lb_f as the rotary speed is increased from 0 to 600 rpm. The 12-1/4-in. carbide insert bits require approximately 800 ft-lb_f torque at 20 000 lb_f bit weight to drill granite, so a flow rate of 370 gpm should be adequate at a turbodrill rotational speed of about 250 to 350 rpm. This is shown in Fig. 4b. However, it should be noted that in directional drilling some additional torque must be delivered to accommodate the lateral load applied to the bit.

The pressure drop across the turbodrill increases linearly with increased rotary speed, as shown in Fig. 5. At 400 gpm, the pressure drop increases from 705 to 890 psi as the rotary speed is increased from 0 to 600 rpm. These data then suggest that a pressure drop of approximately 800 psi will be required to rotate the 12-1/4-in. insert bit at 250 rpm with a bit load of 20 000 lb_f.

The power output of the turbodrill increases with rpm and passes through a maximum as the rotary speed is increased. At a low flow rate of 280 gpm,

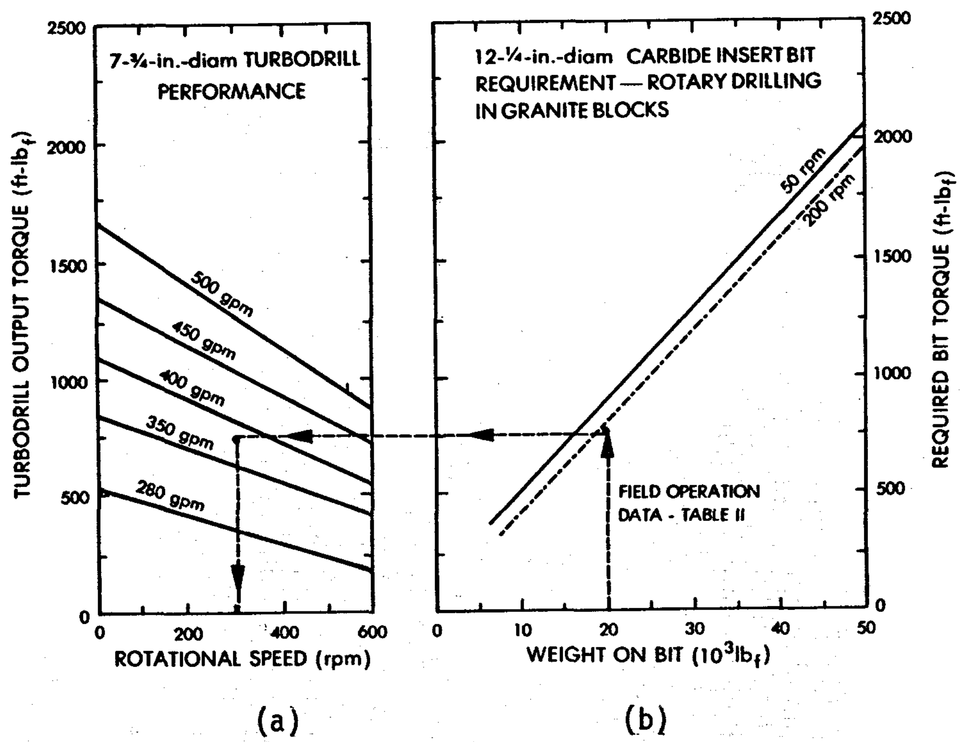

Fig. 4.
Granite rock drilling torque requirements relative to turbodrill operating characteristics.
(a) Turbodrill torque characteristics. (b) Granite rock drilling requirements.

the power output passed through a maximum of 22 hp, at a rotary speed of 400 rpm. With 500 gpm, a maximum power output of 100 hp was reached at a rotary speed of 600 rpm. At higher flow rates, the maximum power output was not reached at 600 rpm.

The load (L_B) on the turbodrill thrust bearings is equal to the bit reaction force (bit weight) (F_B), less the sum of the hydraulic downthrust (F_H) and the rotor weight (W).

$$L_B = \text{Bearing Load} = F_B - (F_H + W) = F_B - \text{Total Downthrust Force } (F_T)$$

with $F_H = \Delta P x A_{eff}$, where ΔP = pressure drop across turbodrill, and A_{eff} = effective cross-sectional area. These forces are shown in Fig. 6. The hydraulic downthrust under stall conditions was measured during the tests conducted at the Terra Tek Drilling Research Laboratory (April 1979). The total downthrust force (F_H + W) increased from 700 to 33 900 lb as the flow rate was

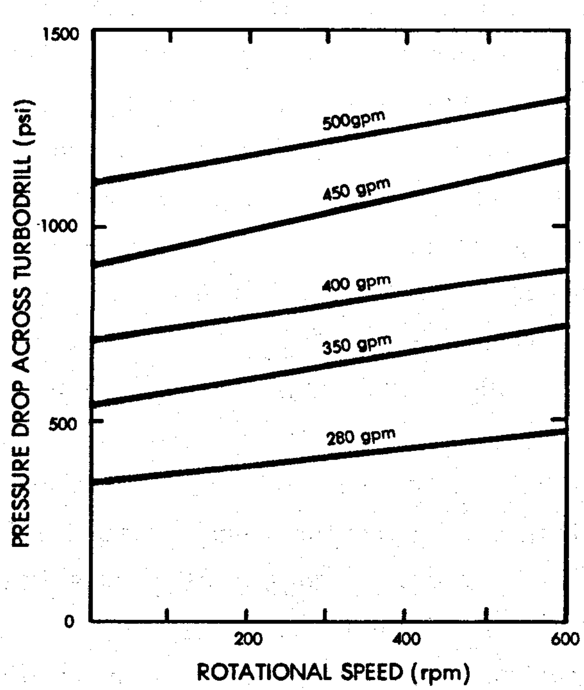

Fig. 5.
Turbodrill pressure drop vs rotational speed characteristics.

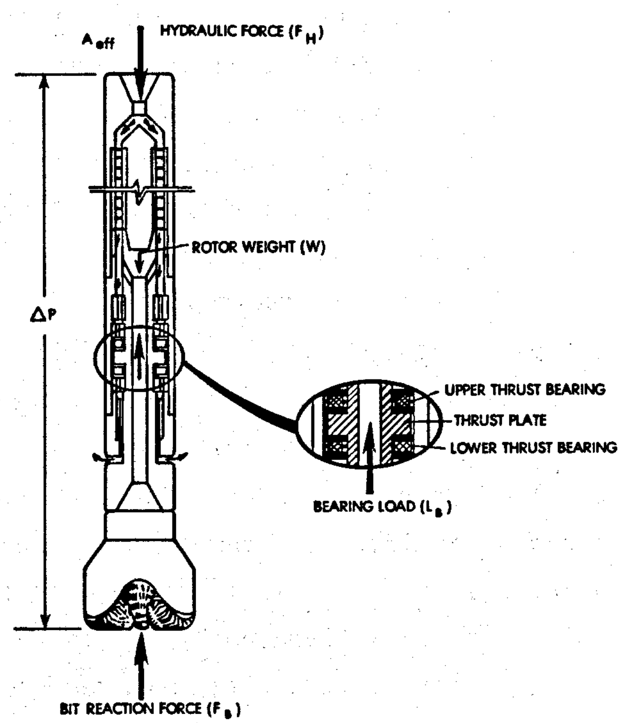

Fig. 6.
Load on turbodrill.

increased from 0 to 500 gpm. The 700-lb downthrust with no flow rate corresponds to the weight (W) of the turbodrill rotor assembly as shown in Fig. 7. At stall conditions, the total downthrust on the rotor shaft increased from 8 500 to 33 900 lb as the flow rate through the 7-3/4-in. turbodrill increased from 200 to 500 gpm. The total downthrust increases with increased rotary speed because of increased pressure drop across the turbodrill. It was noted that the effective area decreased from 39.0 to 29.9 in.^{2} as the flow rate was increased.

The stall torques measured with the dynamometer (Fig. 2) were obtained with full hydraulic downthrust acting on the lower turbodrill thrust bearing. (No bit loads were applied or simulated in the dynamometer facility.) Friction in the thrust bearing therefore reduced the output (measured) torque. During the DRL tests, the output stall torques were measured at balanced load conditions; and therefore,

$$F_{B_0} = F_H + W \quad (L_B = 0\text{, balanced thrust load conditions}),$$

where there is no load on the thrust bearings ($L_B = 0$). In this case, the measured turbodrill output torques were higher than those measured in the dynamometer tests because the lower thrust bearing was heavily loaded in the dynamometer tests. The difference in torque between the two operating conditions corresponds to the friction torque in the bearings as recorded in Fig. 8. The penetration rate determined in the DRL tests drilling in granite blocks (Fig. 9) increased rapidly as the rotary speed was increased (Fig. 10). For example, with 30 000 lb_f bit weight, the drilling rate increased from 5 to 24 ft/h as the rotary speed was increased from 50 to 200 rpm. This indicates that relatively high drilling rates can be obtained in granite with downhole drilling motors. But it must be recalled that higher rpm will result in decreased bit life as compared to rotary drilling. The torque required to drill using a 12-1/4-in. bit in granite is shown in Fig. 4b. Notice that torque was only slightly influenced by rpm in these rotary drilling tests.

The test arrangement used during the turbodrill tests at DRL is shown in Fig. 11. A shock absorber was used beneath the turbodrill to isolate the turbodrill bearings from the high bit impact and vibration loads. Figure 12 is a turbodrill summary performance chart derived from the DRL test data. As

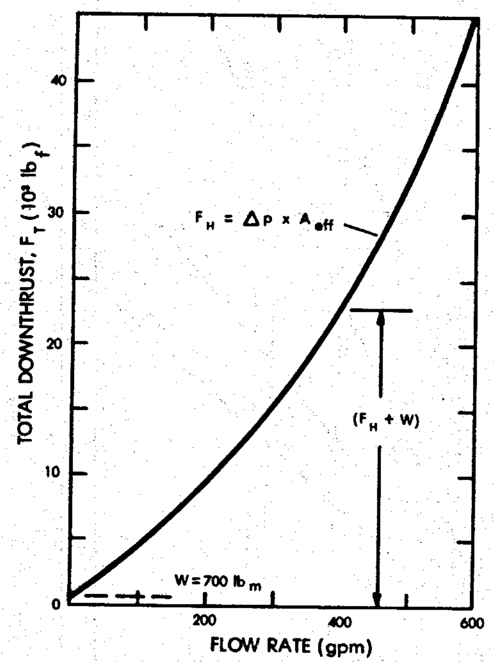

Fig. 7.
Turbodrill hydraulic thrust vs flow rate characteristics.

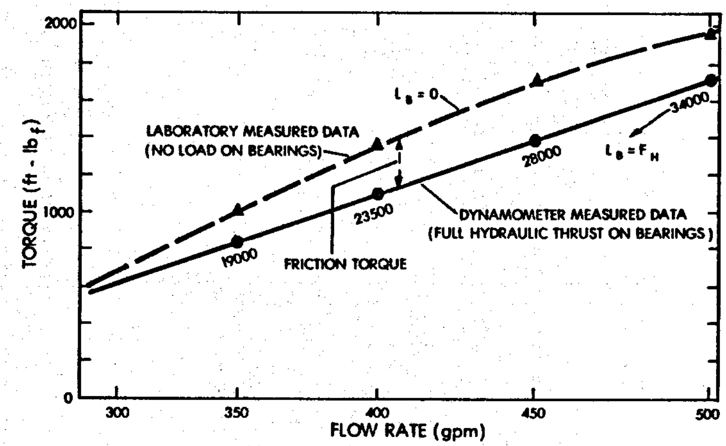

Fig. 8.
Turbodrill bearing friction torque under no load and hydraulic downthrust conditions.

can be seen from these data, the turbodrill achieved all of the performance design targets, except that rpm is higher than desired. The tool remained to be tested in a hot well and under directional drilling conditions.

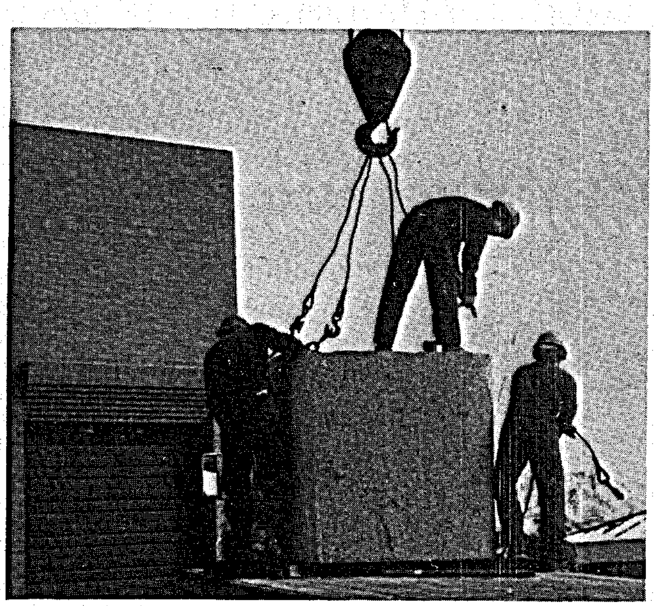

Fig. 9.
Texas pink granite drilling blocks for rotary and turbodrill tests at Terra Tek Drilling Research Laboratory.

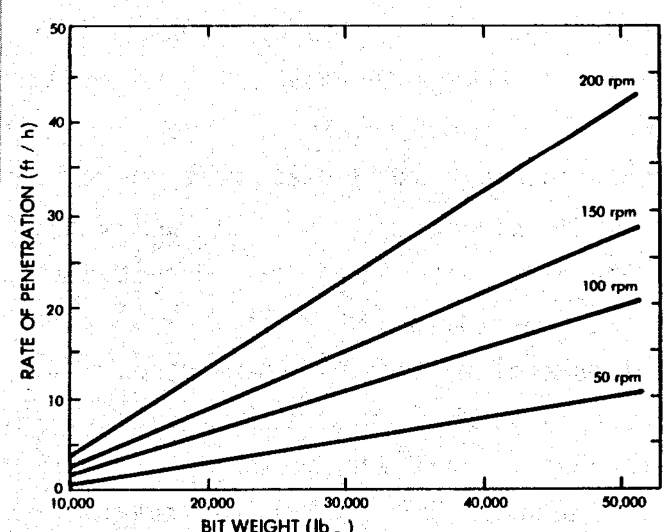

Fig. 10.
Granite drilling penetration rate vs bit weight, 12-1/4-in.-diam bit, at various rpm.

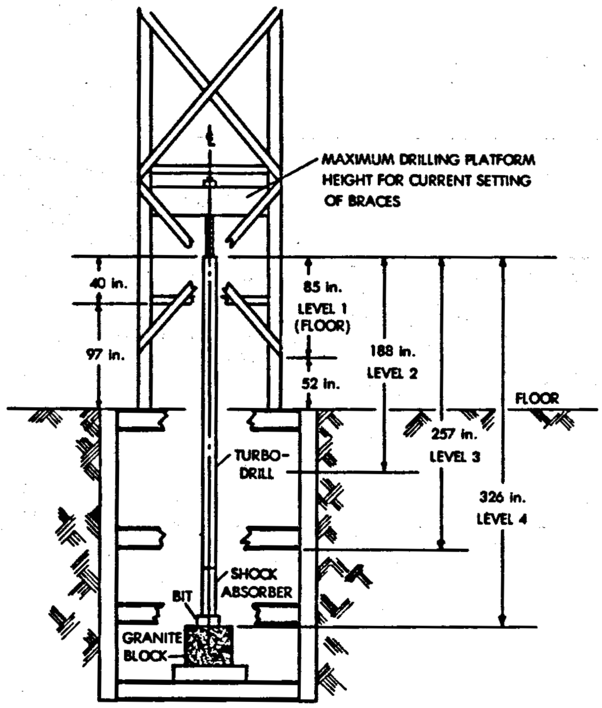

Fig. 11.
DRL turbodrill test setup.

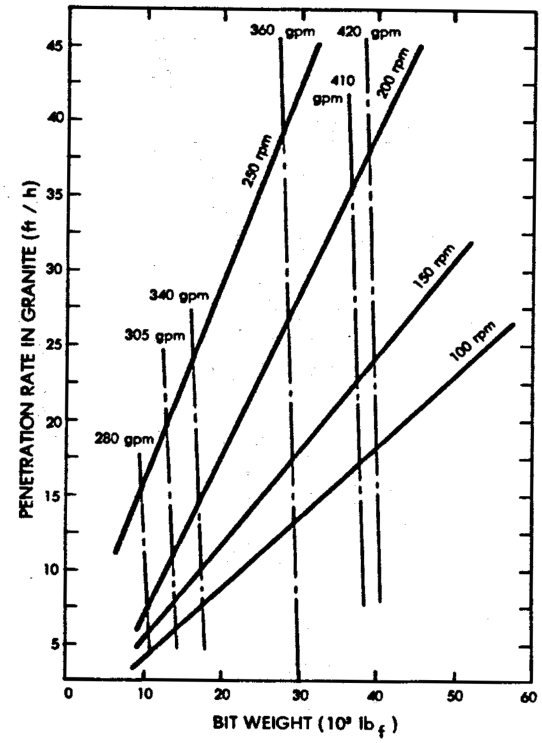

Fig. 12.
Summary of turbodrill performance chart derived from DRL tests.

IV. FIELD PERFORMANCE

The high-temperature turbodrill had its first field trials in July 1979 (see Fig. 13 for view of turbodrill in derrick) and was used to directionally drill in HDR geothermal well Energy Extraction well No. 2 (EE-2). The summary of these field trials is given in Table II. Table III is a typical bottom-hole assembly (BHA) used with the MEI turbodrills. The average performance of the 20 directional runs is shown in Table IV. In reviewing Table IV, it should be noted that the directional drilling procedures generally drilled down two joints (~60 ft) of drill pipe and the bit life was about 120 ft. An example of turbodrill field performance deep in EE-2, at a formation temperature of 220°C, is presented in Table V. (This is Run 21 in Table II.) The turbodrill life was typically greater than the 59.8-ft average run indicated in Table IV because most of the bit runs were terminated because of steering tool problems or bit gauge wear, not as a result of turbodrill failure. A turbodrill would be expected to wear out two to three bits in the hard abrasive granite before the bearings had to be maintained. The two MEI turbodrills were disassembled on site after each directional run in EE-2 (Fig. 14).

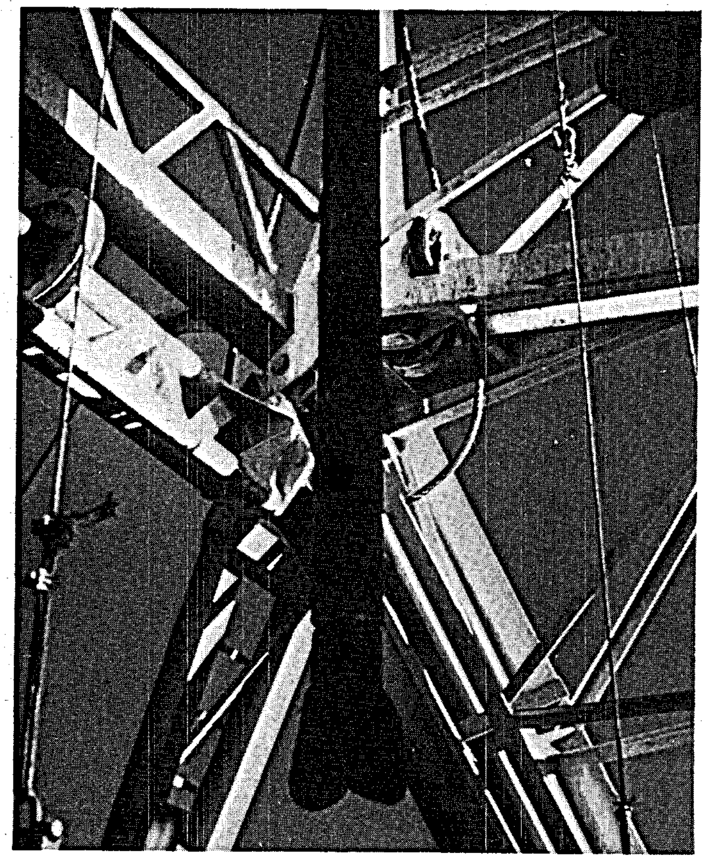

Fig. 13.
MEI turbodrill in derrick for directional drilling run in EE-2.

Fig. 14.
On-site disassembly of 7-3/16-in. MEI turbodrill following directional drill run (using Houston Engineering break-out tool).

TABLE II
SUMMARY OF DIRECTIONAL DRILLING RUNS AND RESULTS FOR WELL EE-2
All runs with 12-1/4-in.-diam bits

Drill Motor Run No.	Steering Tool	Bent Sub Angle	Measured Depth m (ft)[a]	Borehole Inclination and Deviation[b]	Distance Drilled m (ft)	Shock Absorber[c]	Remarks
1	No	-0-	1497 (4912)	5-3/4°,S64°W	17 (57)	Yes	First field trial of 7-3/4-in.-diam MEI turbodrill.
2	Yes	1-1/2°	2538 (8326)	16°,N13°E	17.7 (58)	Yes	All subsequent runs required intermediate reaming of hole.
3	Yes	1-1/2°	2538 (8328)	----	0.6 (2)	Yes	Considerable operational difficulties experienced from 8300-9303 ft with Eastman-Whipstock (DOT)[c] steering tool.[d]
4	Yes	1-1/2°	2564 (8414)	16°,N17°E	26 (86)	Yes	
5	Yes	1-1/2°	2604 (8545)	13-3/4°,N37°E	40 (131)	Yes	
6	Yes	1-1/2°	2613 (8575)	----	9.1 (30)	Yes	
7	Yes	1-1/2°	2613 (8575)	----	-0-	Yes	
8	Yes	2°	2754 (9035)	----	18.3 (60)	Yes	
9	Yes	2°	2754 (9035)	----	-0-	Yes	Turbine would not rotate.
10	Yes	1-1/2°	2768 (9082)	15°,N34°E	13 (42)	Yes	
11	Yes	2°	2800 (9188)	----	32 (106)	Yes	
12	Yes	1-1/2°	2838 (9311)	13-1/2°,N40°E	37.5 (123)	Yes	
13	Yes	1-1/2°	2854 (9363)	13-1/4°,N42°E	15.8 (52)	Yes	
14	Yes/SST[c]	2°	2854 (9363)	----	-0-	Yes	Turbine would not rotate; Sperry-Sun (SST) steering tool failed.
15	Yes	2°	2885 (9467)	12-1/4°,N44°E	32 (104)	Yes	
16	Yes	2°	2900 (9513)	12-1/4°,N44°E	14 (46)	Yes	
17	Yes	2°	2905 (9531)	----	5.5 (18)	Yes	Reached temperature limit of shock absorbers.
18	Yes	2°	2980 (9776)	13°,N59°E	3.0 (10)	No	
19	Yes	2°	3021 (9912)	13°,N59°E	19 (62)	No	
20	Yes	2°	3059 (10,035)	----	36 (118)	No	
21	Yes	1-1/2°	3216 (10,552)	21°,N70°E	38.7 (119)	No	Motor run used to increase inclination.

[a] Depth at end of run.
[b] Based on single-shot magnetic surveys.
[c] Refer to Williams et al., 1979, Ref. 1.
[d] Most of the motor runs were terminated because of steering tool failures or bit gauge wear, not as a result of turbodrill problems.

TABLE III

TYPICAL BOTTOM-HOLE ASSEMBLY FOR FIELD TRIALS
OF 7-3/4-IN.-DIAM TURBODRILLS

12-1/4-in.-diam bit

Shock absorber

Turbodrill

Float valve

Crossover sub

Bent orienting sub [a]

8-in.-diam Monel collar

Twelve 8-in.-diam drill collars

Twenty-one joints of HWDP [b]

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[a] 1-1/2° or 2° bent sub
[b] Drilco HEVI-WATE drill pipe; 5-in. o.d. at 50 lbm/ft.

TABLE IV

AVERAGE FIELD PERFORMANCE, WELL EE-2,
7-3/4-IN.-DIAM TURBODRILL ASSEMBLY AND DIRECTIONAL SYSTEM

Number of Directional Runs	Average Footage [a] Per Run (ft)	Average Hours Per Run (h)	Average ROP [b] Per Run (ft/h)
21	59.8	2.8	21.6

[a] Note that average footage per run was determined primarily by bit wear characteristics and the directional drilling procedure of drilling ahead only two joints ($\sim$60 ft) of drill pipe per run.
[b] ROP = Rate of penetration.

The operating data from Table V are plotted on Fig. 3 to show the interactions between required torque at the drill bit and torque output of the turbodrill, that is, 750 ft-lb_f.

The turbodrill field operational map is depicted in Fig. 15, where the field data have been plotted on the same graph as the DRL test results (Fig. 12). It is emphasized that the bit drilling characteristics are those of the 12-1/4-in.-diam bits obtained in the DRL tests in Texas pink granite blocks.

The directional drilling operational problems at the present time (January 1980) center primarily around inadequate high-temperature steering tool instrumentation to set and monitor turbodrill direction. Excessive bearing wear in the turbodrill is the downhole motor limitation of most concern. Bits should be developed that would have extended life at turbodrill rotational speeds of 300-450 rpm.

An outline for turbodrill operation procedure is presented as Appendix C.

V. FUTURE DEVELOPMENT PROSPECTS

Several directions to achieve improved directional drilling performance have been indicated by this development project.

A. Turbodrills

1. Bearing life could be extended if an effective method of sealing the bearings in a high-temperature oil or grease could be developed. MEI has a continuing effort in this area.

2. Improved bearing designs and configurations may be possible.

3. Reduced turbodrill rotary speed would enhance bit life. One approach is to use a planetary reduction gear system. The higher torque obtained from the reduction gear would also be useful for using drag bits, such as diamond or polycrystalline diamond compact (for example, GE Stratapax®) bits.

B. Instrumentation

Sperry Research Center, Sudbury, Massachusetts, is investigating a rotary speed measurement system developed by MEI.[5] Initial field trials have shown promise. See Appendix D for details of this system.

C. Drill Bits

The bits used with the turbodrill to date have shown excessive wear on bearings and gauge surfaces (maximum diameter) and bit life was usually less than turbodrill life. Improved high speed roller-cone bits would be desirable. Long life and high drilling rates would be possible if a suitable PDC (Stratapax®) bit were available.

TABLE V

SUMMARY DATA FOR LAST TURBODRILL RUN,[a] WELL EE-2

Date: October 12-13, 1979.

Depth: 10 433 to 10 552 ft.

Drilling Interval: ~119 ft.

Approximate Formation Temperature: 220°C.

Shock Absorber: None

Bit: Smith Tool Co. Q9JL (12-1/4-in. diam).

Bit Load: ≤20 000 lb_f.

Bent Sub: 1-1/2°.

Flow Rate: 77 pump strokes/min. ~360 gpm.

Estimated Rotary Speed: 300-400 rpm.

Inclination Angle Change Achieved: ~4°.

Total Rotating Time: >4.5 h.

Nominal Penetration Rate: >26 ft/h.

Condition of Bearing: No broken races, with estimated ≥1/2-h drilling life remaining in radial bearings.

Other Data: No flow meter or pump desurgers were used; run was in two segments: 3-h drilling, interrupted by ~3/4-h interval for steering tool problems, followed by ~1-1/2-h drilling time.

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[a]See Run 21, Table II, turbodrill and directional system used to build inclination.

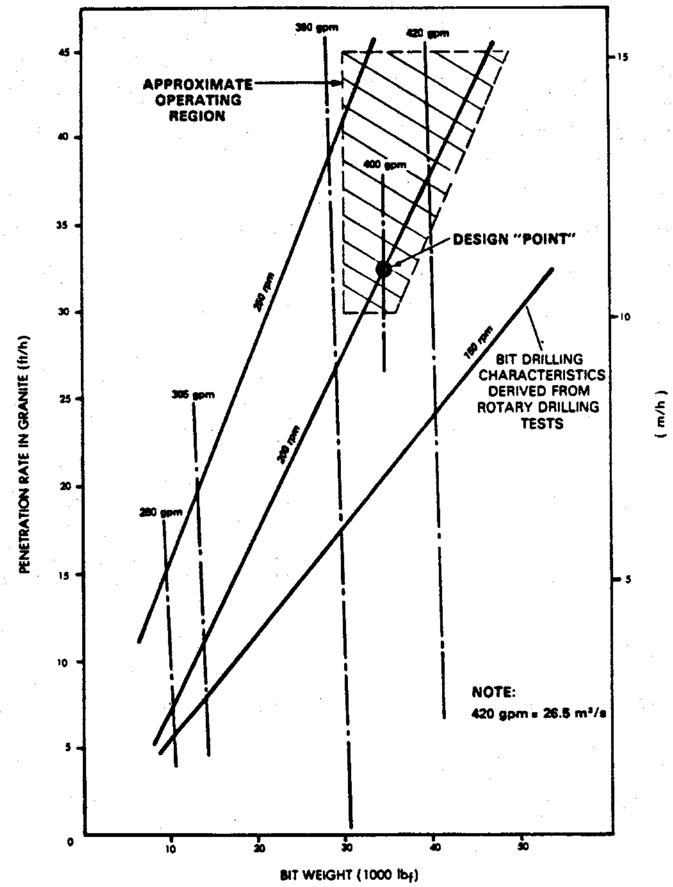

Fig. 15
Turbodrill field operational map.

COMMERCIAL AVAILABILITY

The MEI turbodrills are now available commercially through ONCOR Drilling Tools (Houston, Texas) in the U.S., and Komatzu, Ltd. (Tokyo, Japan) in southeast Asia. For more information, contact William C. Maurer, Maurer Engineering, Inc., 2916 West T. C. Jester Blvd., Houston, TX 77018; telephone 713-683-8227.

ACKNOWLEDGMENT AND DISCLAIMER

The authors wish to thank the many firms and individuals that supported the turbodrill 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 (Los Alamos National Laboratory) or the U.S. Department of Energy to the exclusion of others that may be suitable.

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5. McDonald, W. J., W. C. Maurer, J. W. Neudecker, and H. D. Shoemaker, "Development of a Turbodrill Tachometer," Transactions, Geothermal Resources Council, September 1980, Vol. 4.

APPENDIX A

ASSEMBLY INSTRUCTIONS

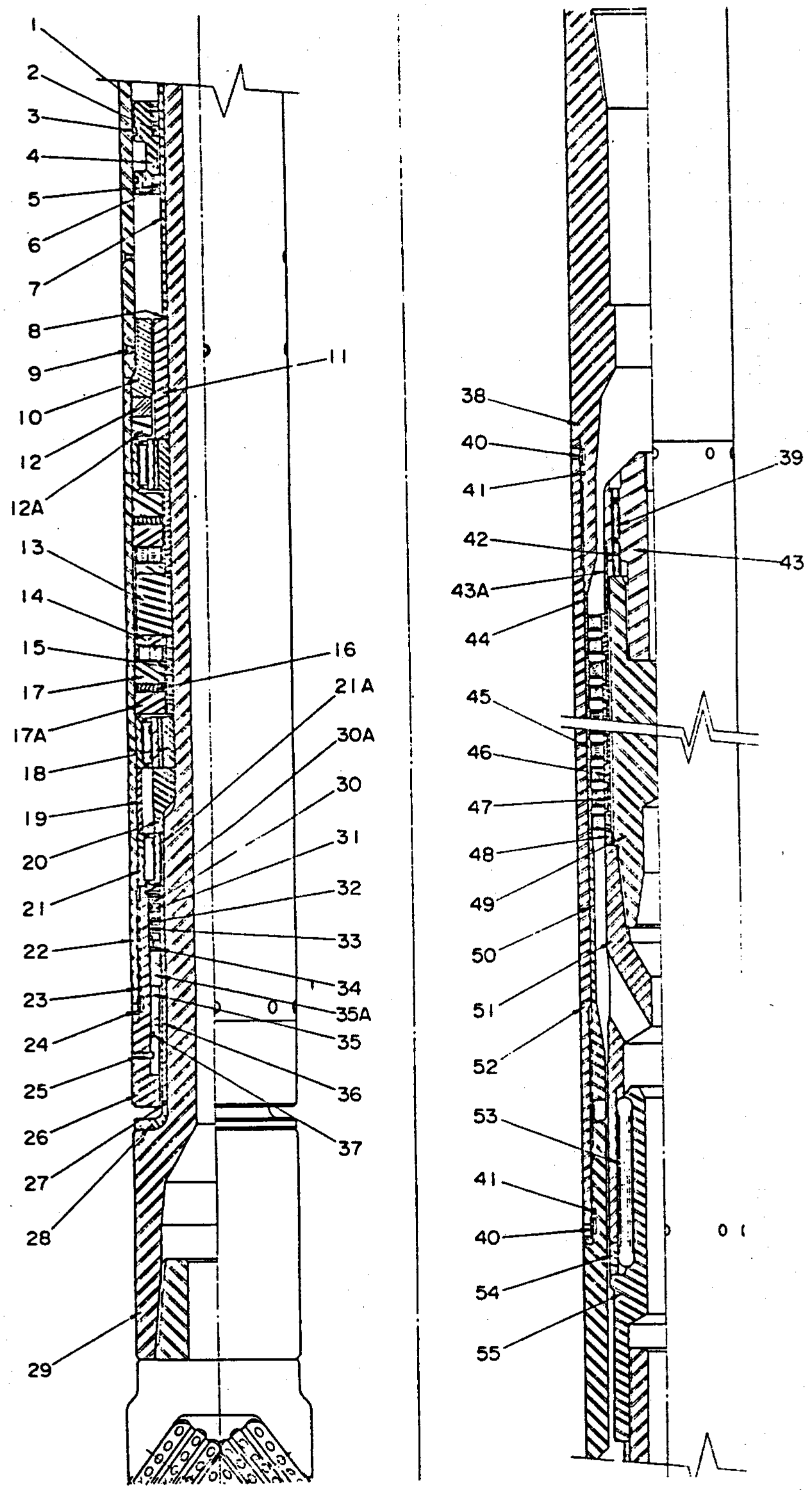
The assembly of the turbodrill should be carried out in strict accordance with the following two manuals prepared by Maurer Engineering, Inc.

1. MEI TR 79-16 dated May 7, 1979: Assembly Manual, 7-3/4-in. Bearing Pack and Turbine, by John H. Cohen, Jeddy D. Nixon, and David D. Nagel.
2. MEI TR 79-17 dated May 7, 1979: Assembly Instructions for 7-3/4-in. Bearing Pack and Turbine Lower Seal Assembly and Upper Seal Assembly.

APPENDIX B

SECTION VIEW AND PARTS LIST

MEI 7-3/4-IN.-DIAM TURBODRILL



PARTS LIST

Index No.	Part No.	Description	Quantity
	80-96	FLOATING PISTON ASSEMBLY (Variseal)	1
1	80-87	- VARISEAL, floating piston	2
2	80-88	- VARISEAL, floating piston	1
3	P1-437-1	- O-RING	2
4	80-80	- BODY, floating piston	1
5	80-81	- BUCK-UP RING	3
6	80-89	- SPIROLOX, floating piston	2
7	77-64	- SLEEVE, bearing shaft	1
8	P1-042-1	O-RING	1
9	77-62	PLUG, pipe	4
10	77-62	SPACER, ring, housing upper	1
11	77-35	SLEEVE, bearing shaft	1
12	80-34	SPACER, bearing housing	1
12A	80-196	SPACER, bearing housing	1
13	77-31	SPACER, thrust bearing	
14	78-303	THRUST BEARING ASSEMBLY	2
15	77-26	SLEEVE, bearing shaft	2
16	77-9-1	DISK, spring	8
17	80-195	RETAINER	2
17A	77-27	RETAINER	2
18	77-159	SLEEVE, radial bearing	2
19	77-28	SPACER, bearing housing	1
20	77-23	SPACER, ring, shaft upper	1
21	78-758	RADIAL BEARING ASSEMBLY	3
22	77-61	HOUSING, bearing pack	1
23	P1-364-1	O-RING	1
24	77-19	RING, lower lock	1
25	78-644	SCREW, set	6
26	79-269	BEARING MAKE-UP SUB ASSEMBLY	1
27	P1-046-1	O-RING	1
28	77-15	RING, end	1
29	77-55	SHAFT, bearing	1

	80-99	LOWER SEAL ASSEMBLY (Variseal)	1
30	80-95	- VARISEAL, lower seal	4
30A	N5002-625	- RING, retaining	1
31	80-83	- RETAINER, seal end	2
32	P1-360-1	- O-RING	3
33	80-82	- RETAINER, cutter seal	1
34	80-84	- SPACER, back-up	2
35	79-270	- SEAL, labyrinth	1
36	77-16	- SLEEVE, seal	1
37	P1-256-1	- O-RING	1
38	77-53	STATOR HOUSING SUB ASSEMBLY	1
39	77-52	SCREW, set	3
40	77-40	RING, lock	2
41	P1-363-1	O-RING	2
42	77-51	SCREW, set	3
43	77-50	NUT, rotor make-up	1
44	77-49	SPACER, stator	1
45	76-16	BLADE, stator	50
46	76-17	BLADE, rotor	50
47	77-48	WIRE, rotor lock	10 ft
48	77-47	SPACER, rotor	1
49	77-46	SHAFT, rotor	1
50	77-45	SLEEVE, stator make-up	1
51	77-44	END, spline box	1
52	77-43	HOUSING, stator	1
53	77-42	PIN, spline	4
54	77-39	SPACER, spline	1
55	77-38	END, spline pin	1

APPENDIX C

TURBODRILL OPERATION PROCEDURES

I. HOLE CONDITION AND PREPARATION

Hole condition is extremely important to making a directional hole with a turbodrill. The hole must be reamed fully to the gauge of the bit size to be used and must not have "tight" sections or bad doglegs. Although a 3-point reamer passed to bottom may be sufficient to get a satisfactory hole, it is better to use a stiff assembly consisting of one (or more) 6-point roller reamers freely operated to bottom of the hole before starting to drill with a turbodrill.

It is advisable to circulate the hole completely for about 2 h and to sweep the cuttings with a high viscosity gel pill before a turbodrill run.

II. TURBODRILL BOTTOM-HOLE ASSEMBLY

In a typical BHA for directional drilling with the turbodrill, it is extremely important to include the float valve, which is inserted in a sub immediately above the turbodrill. This float prevents reverse flow and subsequent damage to or plugging of the turbodrill with cuttings. A second float added in a sub immediately above the turbodrill will give added protection. High-temperature elastomer seats are required in the seals.*

The bent sub may be up to 2°, but 1-1/2° is recommended.

III. TURBODRILL INSERTION PROCEDURES (TRIPPING IN)

At surface, hang turbodrill from circulating head and swivel with bit and shock sub in hole. Increase pump strokes slowly and note fluid flow rate at which turbodrill rotation begins (usually about 50 to 70 gpm). If turbodrill rotates freely, disconnect swivel and continue tripping toward bottom.

Stop and fill drill pipe every 20 or 30 stands.

At bottom, raise string from bottom about 15 ft, connect swivel, and start flow to ensure turbodrill rotation.

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* Bakerline (San Antonio, Texas) has developed a geothermal (600°F, 300°C) seal kit for their line of float valves.

IV. START OF DRILLING

This start-of-drilling procedure should be followed at time of initial drilling and at every interruption of drilling, such as adding a stand of pipe, adjustment of directional instrument, or resumption of drilling after "stalling out" turbodrill on bottom.

1. Raise turbodrill 10 ft or more off bottom.
2. Start flow at approximately 250 gpm.
3. Lower turbodrill to touch bottom. Do not exceed 5000 lb_f bit weight.
4. Increase flow to approximately 400 gpm.
5. Raise bit weight to 10 000 lb_f. Observe drill-off (establish an ROP) to verify drilling; a pressure increase of about 125 to 150 psi will indicate drilling has started.
6. Raise bit weight in 5000-lb_f increments (10 000, 15 000, 20 000 lb_f, etc.).
7. Try to establish steady drilling at approximately 20 000 to 25 000 lb_f of bit weight.
8. If turbodrill stalls out, drill-off will indicate no penetration rate and a decrease in pressure of about 125 to 150 psi.
9. If turbodrill stalls, lower bit weight by at least 5000 lb_f and try to restart, verified by drill-off. If turbodrill will not start, reduce flow rate to 250 gpm and pull up off bottom.
10. Go back to Step 1 and repeat sequence.
11. If steady-state drilling is achieved, consult with directional driller to see if tool face angle is acceptable.
12. Small correction to tool face angle may be achieved by small adjustments in flow rate.
13. If large corrections of tool face angle are required, stop turbodrill by Step 9 above and follow instructions of directional driller to make corrections; for example, rotate rotary table with slips on drill pipe.

V. DIRECTIONAL ADJUSTMENTS

The directional driller will orient downhole assembly before insertion.

During drilling the directional driller will note drilling progress by the steering tool and will suggest to the driller the corrections that can be made by small changes in flow rate.

Large changes in azimuth, after drilling is started, will require turbodrill shutdown (Step IV-9) and reorientation of string.

To start turbodrill after reorientation, go back to Step IV-1 and repeat sequence.

VI. STEADY-STATE DIRECTIONAL DRILLING

1. Directional driller will follow progress by referring to his tool face indicator.
2. Make small adjustments by changing flow rate slightly.
3. Note drilling progress by chalk marking string at surface.
4. Acceptable drilling rates are 20 to 60 ft per hour.

VII. DRILLING INTERRUPTION AND RESTARTING

If drilling is interrupted for any reason, follow shut-down procedure of IV-9 above and when drilling resumes, follow start-up procedure beginning with Step IV-1.

VIII. TURBODRILL END OF RUN

Normally turbodrill runs stop when the bit wears out and drilling rate goes to zero. This can happen either gradually or suddenly. Usually, the drilling rate decreases approximately 50% just before it stops completely. When drilling stops, follow Step IV-9 for turbodrill shutdown. Other reasons for termination of a run may be that a sufficient correction has been made, a steering tool has malfunctioned, a turbodrill has blocked, etc.

IX. TURBODRILL EXTRACTION

1. Maintain a small flow, approximately 250 gpm, to pull turbodrill up from bottom as high as string permits. Shut off flow. Pull up slowly and steadily. Do not jerk up. Do not exceed approximately 100 000 lb_f (over string weight) during extraction. Trip out per standard rig procedures.

2. When tripping out is completed, attach swivel and verify that turbodrill turns by pumping a small flow through bottom-hole assembly. See inspections below.

X. INSPECTIONS

1. After tripping out, start flow to turn turbodrill. Compare flow rate required to turn at end of run with flow to turn at beginning of run.
2. Inspect bit for wear information.
3. Inspect turbodrill after each run for evidence of bearing or turbine wear. If significant wear is found, turbodrill is to be disassembled and refurbished.

APPENDIX D

TURBODRILL TACHOMETER*

I. INTRODUCTION

The short-length, high-torque turbodrills for geothermal directional drilling operations can operate at any speed from stall to runaway, depending on load on bit. Maximum torque is developed at stall and the torque decreases toward zero at high speeds (Fig. D-1). In the field, turbodrill speed is controlled by bit torque, which is in turn related to weight on bit. During direction drilling, it is sometimes difficult to know and control weight on bit, particularly in inclined holes. Excessive weight on bit can lead to stalling of the turbodrill, whereas with too little thrust, motor speed can become high. It is particularly important in the EE-2 directional operations to operate the motor at relatively low speeds to extend the life of the carbide insert roller bits used in drilling granite. In order to control turbodrill speed within a practical range, a rpm tachometer system was developed.

II. OPERATING PRINCIPLE

A fluid pulse generator tachometer was developed for the MEI 7-3/4-in. turbodrill. The pulsing tachometer produces one pressure pulse each time the turbodrill rotates one revolution. These pressure pulses are transmitted through the drilling fluid in the drill pipe to the surface. Instrumentation on the rig floor monitors the frequency of the pressure pulses. This frequency is a direct and continuous measure of the turbodrill speed.

The pressure pulses are produced by blanking approximately 40% each of the first stage of the turbine inlet rotor and stator.

As the rotor turns on the turbine shaft, the blanked spaces pass over those in the stationary stator. The total flow area thus varies cyclically as the turbine shaft rotates. When the blanked blades are in line, 40% of the flow area is blocked, whereas when the blanked areas are offset, 80% of the

*This work was supported in part by Morgantown Energy Research Center, DOE, under contract No. DE-AC21-79MC11251, to Maurer Engineering, Inc. Sperry Research Center, Sudbury, Massachusetts, participated in this development.

flow area is blocked. This momentarily restricts flow through the blades and produces a pressure pulse that can be detected at the surface. The pressure pulse appears sinusoidal at the surface and in phase with the changing blade area as shown in Fig. D-2.

III. SYSTEM

In addition to the blanked turbine blades, there are four surface components to the pulse tachometer system: rig pumps, desurgers, pressure transducer, and spectrum analyzer.

Standard rig pumps were used. No changes were made to the rig pump or to the circulation system except for the addition of pressure desurgers in the pump outlet flow lines.

The pumps used on rotary drilling rigs produce severe pressure fluctuations (±100 to 400 psi). This noise masks the pressure pulses produced by the pulsing tachometer blades. Hydrodyne Industries 10-gal. desurgers (Type AA30-10) were used to reduce the pump noise. In these, nitrogen acting against a rubber bladder absorbs the flow rate variations and reduces the pressure fluctuations. The desurgers are charged to about 70% of the pump

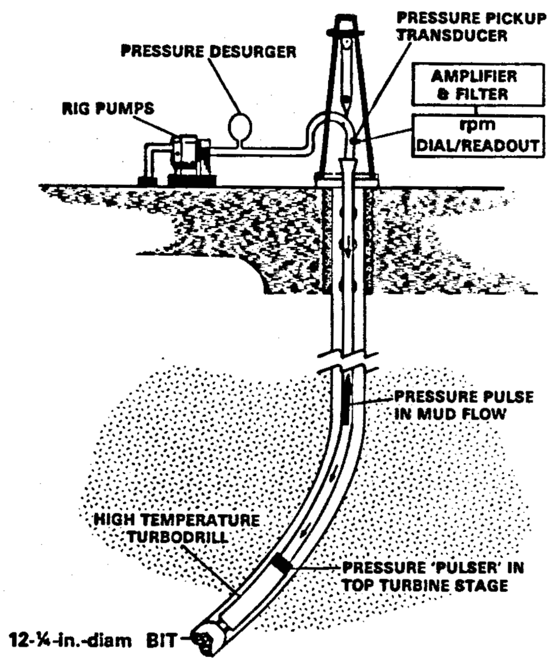

Fig. D-1.
Geothermal turbodrill rpm indicator system.

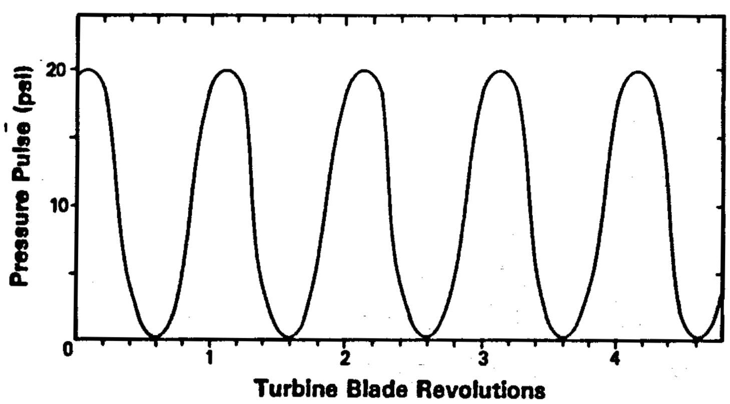

Fig. D-2.
Typical pressure response at surface.

operating pressure for maximum efficiency. Up to four desurgers were used during the field tests. The field tests have shown that good desurgers are essential with the pulse tachometer. Without good, properly charged desurgers, the pulse signals cannot be extracted from pump noise even at shallow depths; with desurgers, the tachometer performed well at depths in excess of 10 000 ft.

In all field tests the pressure pulses were detected using Teledyne-Taber Model 206 0-5000 psi pressure transducers on the standpipe flow line. These transducers utilize DC strain gage bridges that were powered by a Gentran, Inc. Model GT-403G Transducer Indicator. This unit both conditioned the signal and provided an analog readout of steady-state pressure.

Early tests showed that it is not possible to process pressure pulses directly from an oscillograph record of the pressure signal because of the high amplitude of the pump noise, even with desurgers in the flow lines.

A fast spectrum analyzer was used to process the pulse signal. These tests were very successful with desurgers on the flow lines. The spectrum analyzer displays the fundamental and harmonic frequencies of the pump noise in addition to the pulse signal. Since the pump speed (i.e. fundamental frequency) is known, it was possible to differentiate the rpm pulse signal from the pump noise.

Any high quality spectrum analyzer can be used. Both a Nicolet Scientific Corporation Model 466A and a Hewlett-Packard Model 3582A Spectrum Analyzer were satisfactory.

IV. LABORATORY TESTS

The pulse tachometer was tested in the 7-3/4-in. turbodrills in the MEI turbodrill dynamometer test stand. A magnetic pickup tachometer was used to directly measure the rotary speed to the nearest rpm. Two desurgers were used during the laboratory tests. The laboratory tests demonstrated that the pulse tachometer was accurate and reliable at all speeds. In all tests, the electrical and pulsing tachometers agreed within a few rpm.

V. FIELD TESTS

The fluid pressure pulse tachometer was tested and used for the EE-2 directional drilling. Water was used as the drilling fluid on this well. The pulse tachometer performed very well during these tests to depths in excess of

10 000 ft. Attenuation of the signal transmitted up the drill pipe was not a problem.

Although the pump noise produced several spikes on the spectrum analyzer record, it was easy to differentiate the tachometer signal from the pump noise for four reasons: (1) the fundamental pump speed was known; (2) the pump noise produced several harmonics that helped identify them; (3) the rpm pulse signal slowly moved back and forth on the spectrum analyzer as the turbine speed varied, whereas the pump signal remained constant; and (4) the pump signal produces steep spikes, whereas the pulse signal produced a broader peak. The drillers and rig crew quickly learned to identify the pulse signal and to use the tachometer as a tool to optimize the field operation of the turbo-drills.

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