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LABORATORY AND FIELD TESTING OF IMPROVED GEOTHERMAL ROCK BITS

R. R. Hendrickson
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Terra Tek, Inc.

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department of
Energy under Contract DE-AC04-76DP00789

July 1980

Work performed under Sandia Contract No. 13-8783
for the Geothermal Drilling and Completion
Technology Program for the Department of Energy,
Division of Geothermal Energy

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Printed July 1980

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Printed in the United States of America
Available from:
National Technical Information Service
U. S. Department of Commerce
5825 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$4.00; Microfiche \$3.00

* Work performed under Sandia Contract 13-8783 for the United States
Department of Energy, Division of Geothermal Energy.

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ABSTRACT

The development and testing of 222 mm (8-3/4 inch) unsealed, insert type, medium hard formation, high-temperature bits are described herein. The new bits were fabricated by substituting improved materials in critical bit components. These materials were selected on bases of their high temperature properties, machinability, and heat treatment response. Program objectives required that both machining and heat treating could be accomplished with existing rock bit production equipment.

Two types of experimental bits were subjected to laboratory air drilling tests at 250° C (482° F) in cast iron. These tests indicated field testing could be conducted without danger to the hole, and that bearing wear would be substantially reduced. Six additional experimental bits, and eight conventional bits were then subjected to air drilling at 240° C (464° F) in Franciscan Graywacke at the Geysers, CA. The materials selected improved roller wear by 200 percent, friction-pin wear by 150 percent, and lug wear by 150 percent.

Geysers drilling performances compared directly to conventional bits indicate that in-gage drilling life was increased by 70 percent. All bits at the Geysers are subjected to reaming out-of-gage hole prior to drilling. Under these conditions the experimental bits showed a 30 percent increase in usable hole over the conventional bits. These tests demonstrated a potential well cost reduction of 4 to 8 percent. Savings of 12 percent are considered possible with drilling procedures optimized for the experimental bits.

Industrial participation in the program included Reed Rock Bit

Company, Inc., which fabricated the prototype bits, and Union Geothermal Division of Union Oil Company, Inc., which provided the field drilling site. The program was funded by the U. S. Department of Energy, Division of Geothermal Energy, under the direction of Sandia Laboratories.

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INTRODUCTION

The program goal was to reduce geothermal well costs, particularly for the more difficult geothermal sites, by accelerating commercialization of improved geothermal unsealed roller-cone bits. Geothermal drilling is currently done with conventional roller-cone rock bits and related equipment which were developed for oil and gas drilling. Geothermal drilling conditions frequently result in a drastic reduction in drill bit life due to the high temperatures, strong abrasive rock, and/or the use of air as the circulating fluid. The time wasted in replacing worn bits greatly increases the well cost over than of a similar non-geothermal well. Bits are needed that can provide improved life in severe geothermal applications. The D. O. E. Division of Geothermal Energy therefore initiated a program to improve the temperature and gage-cutting capabilities of unsealed rock bits. The program was directed by the Geothermal Drilling and Completions Division of Sandia Laboratories.

DESCRIPTION OF EXPERIMENTAL AND CONVENTIONAL DRILL BITS

The size of the geothermal bit market cannot presently justify expenditure by the bit manufacturers for design modifications and related factory tooling. The market is, however, sufficient to support manufacturing of bits from alternate materials, provided these can be forged, heat treated, carburized and machined with available equipment. The experimental bits fabricated for this program were therefore geometrically identical to conventional Reed Y73 JA medium-hard formation bits; the latter were used as the standard comparative bit in the field tests.

The design goal for the experimental bits was the capability for air drilling at 300° C (572° F) under full load (200 KN or 45,000 pounds) with improved gage-cutting ability. The materials properties requirements were established by:

- Identifying failure modes of bits recovered from geothermal drilling operations; ^{1, 2,} and,
- performing materials properties tests at temperature on candidate steels and cemented carbides; ^{3, 4,} and
- fabrication and laboratory testing of two previous generations of experimental bits at 310° C (600° F). ^{5, 6}

The materials properties requirements are presented in Table I along with the properties of the materials actually selected. Note that two types of experimental bits (four of each) were constructed to evaluate two different friction-pin bearing systems.

TABLE I
MATERIALS PROPERTIES REQUIREMENTS
for 300° C (572° F) AIR DRILLING, AND PROPERTIES
OF SELECTED MATERIALS

COMPONENT	REQUIRED HARDNESS, (ABRASION RESISTANCE) ¹	REQUIRED YIELD STRENGTH GPa (ksi)	REQUIRED FRACTURE TOUGHNESS Mpa√m (ksi√In)	MATERIAL USED	HARDNESS (ABRASION RESISTANCE) ¹	YIELD STRENGTH GPa (ksi)	FRACTURE TOUGHNESS, Mpa√m (ksi√In)
LUGS	R _C 50	0.69 (100)	100 (91)	TIMKEN CBS-600	R _C 55	1.05 (152)	75 (68)
CONE BODIES	R _C 50	1.00 (150)	90 (82)	AISI 4820 ²	R _C 45	NA	NA
ROLLERS AND BALLS	R _C 50	1.70 (250)	25 (23)	AISI M-500R _C 56	R _C 50	1.70 (250)	30 (27)
FRICTION PIN BUSHING	R _C 50@ 600° C	--	20 (18)	AISI M-500R _C 64 ³	R _C 52@ 550° C	1.70 (250)	18 (16)
FRICTION PIN BUSHING	R _C 50@ 600° C	--	20 (18)	Carboloy # 248 ³	R _A 88.6 (7) ¹	3.10 (450)TRS ⁴	11 (10)
GAGE INSERTS	(12) ¹	--	12 (11)	Carboloy # 90	R _A 89.0 (7) ¹	2.40 (350)TRS ⁴	12 (11)
OTHER INSERTS	(7) ¹	--	12 (11)	Carboloy # 231	R _A 87.8 (4) ¹	2.80 (400)TRS ⁴	15 (14)

1. Rockwell A hardness and ANSI/ASTM B 611-76 Abrasion Resistance for the cemented carbide components are at room temperature.
2. Cone bodies were of the standard material but CBS-600 could also be used.
3. Four experimental bits of each type were constructed.
4. Transverse Rupture Strength.

LABORATORY GEOTHERMAL AIR DRILLING TESTS

One experimental bit of each of the two types, and one conventional bit, were subjected to laboratory drilling tests at temperature to determine bearing wear, and to reveal any cataclysmic failures which could "leave iron in the hole" at the field test site.⁶ The bits were evaluated in Terra Tek's Drilling Research Laboratory, utilizing the newly developed geothermal air drilling test system (Figures 1 and 2). The drill rig provides the required weight-on-bit* and rotary speed, while torque, penetration, rotary speed, weight-on-bit, and air temperature are monitored and recorded.

The Geothermal Air Drilling Test Facility consists of a diesel-powered air compressor, gas-fired heater, hot air swivel, and insulated drill collars. The airflow maintains the drill bit and cast-iron pad at the required test temperature; the airflow also removes the drilled cuttings from the pad and provides† the necessary purging through the bearings.** The shroud (Figure 2) directs the effluence down the outside of the pad where it discharges through slots; this enhances pad heating, reduces noise, and confines the cuttings.

TEST PROCEDURE: All bits were run with 12.7 mm (0.50-inch) nozzles and an airflow rate of 20 M³/min (700 CFM); the resulting pressure drop across the bit was 0.28 MPa (40 psi). The test temperature was 250° C (482° F), as measured in the effluent air stream at the top of the test pad.

* Drilling is generally done at a constant (servo-controlled) load, but may be controlled manually or with an external input to the servo system to further simulate drill string dynamics.

** In an unsealed bit, part of the circulating fluid is directed through the three cutters to cool and purge the bearings.

The test pads were of grade GC-35 meehanite (gray cast iron), which has a minimum transverse rupture strength of 240 MPa (35 ksi). The strength and ductility of the iron caused slow drilling, thus insuring adequate pad life for the duration of the test. The cast iron outlasts a rock such as granite by a factor of 250 to one, but is not intended to test the abrasion resistance of the drilling inserts. Rock samples could be used for evaluation of penetration rate, specific drilling efficiency, chip formation, or wear of the cutting structure.

Figure 1.
Experimental 222 mm
(8-3/4 inch) unsealed
bit on cast-iron test pad.

Figure 2.
Geothermal air
drilling test system
with shroud in place.

The conventional Y73 JA was run at 133 KN (30,000 pounds) until failure occurred at 18 hours. The two experimental bits were then run for 18 hours under the same conditions as the Y73 JA. All three bits were then disassembled for wear measurements; these data are presented later in this report. The two experimental bits were then reassembled* and run an additional 18 hours to insure that the bits would not fail cataclysmically and leave "iron in the hole" during field testing. Intermittent cone locking was observed near the end of both runs, but no inserts or other parts were lost.

* The two experimental bits used for laboratory testing were of take-apart construction.

FIELD DRILLING TEST CONDITIONS

Arrangements were made with Union Geothermal, Inc., of Santa Rosa, California, for field-testing of six experimental bits, and at least six comparative bits. The tests were conducted at the Geysers, California, with Loffland Brothers, Inc., as drill rig operators. Since Reed Y73 JA bits are routinely used, the comparative bits represented current practice for Geysers drilling, in addition to being geometrically identical to the experimental bits. The Geysers drilling conditions (listed below) provided an ideal test site, since nearly all factors known to adversely affect bit life were present: ⁷

1. Air drilling at Formation Temperatures - The drilling air attains the formation temperature of 240° C (464° F) by the time it reaches the bit. The lower rate of heat transfer provided by air results in excessive localized frictional heating at points of contact, particularly the friction pin and lug roller race.
2. Hard Formations - The hard formations such as Granodiorite and Chert require high bit weights to crush the rock, resulting in excessive bearing wear and insert breakage.
3. Abrasive Formations - Abrasive formations such as Graywacke and Serpentine cause severe wear of the gage-cutting structure.
4. Inclined Faults and Dips - Bit weight must be reduced, with resulting increase in gage wear per distance drilled.
5. Swelling - Swelling of previously drilled hole requires reaming, resulting in wear on the gage cutters and ball bearings.

The two types of experimental bits, and the conventional bits were run alternately in order to minimize the influence of variable drilling conditions.

All experimental bits and conventional bits used in the analyses drilled with a weight-on-bit between 89 KN and 165 KN (20,000 and 35,000 pounds). The lighter weights were used to reduce deviation, especially when more "sinking" i.e., return to vertical drilling was required, or when the drill followed, rather than penetrated the strata.

Trip lengths are determined by the drilling superintendent's estimate of gage loss, which is based on the hours of reaming, hours of drilling, penetration rate, weight-on-bit, rotary speed, and formation drillability. Bits are generally pulled when the gage loss is estimated to be 5.0 mm (0.20 inches). It was therefore not advisable to increase the drilling time for the experimental bits, since there was no way of knowing how much gage loss had occurred.

PERFORMANCE ANALYSES

The first section, "Bearing Wear", compares the bearing performance for the experimental and conventional bits in both the laboratory and field drilling tests. The second section, "Drilling Performance", compares their overall drilling performance at the field test site. The "Reamer Performance" section discusses the bit performance in conjunction with the other elements of the bottom-hole-assembly.

Bearing Wear

All bits (8 experimental and 8 conventional) were disassembled and measured for wear, as illustrated in Figure 3. In addition, six balls and six rollers from each lug/cone set were fully characterized.

The laboratory bits were subjected to 133 KN (30,000 pounds) load and 250° C (482° F). The field tests averaged 2.8 hours of reaming and 19 hours drilling at 240° C (464° F) and 133 KN (30,000 pounds) load for both the experimental and conventional groups (see Table II). Direct comparisons of bearing wear are therefore possible; the bearing wear data for the laboratory tests are presented in Figure 4, and the field-test bearing wear data in Figure 5. In each bar graph, the wear indicated is the average of all three sets from all bits within that group.

In comparison, the Geysers tests demonstrated significantly greater improvement for the experimental bits than was observed in the laboratory. The largest wear differences were in the friction pin and ball bearing systems. These are attributable to two factors:

- The reaming experienced by the field-test bits; and

Figure 3. Wear measurement locations.

- The in-thrust on the cones for the field tests, and the lack of it in the laboratory tests.*

The combined lug, roller and cone wear in the roller bearing systems are similar, but the roller races on the experimental lugs experienced approximately 40 percent less wear in the field than in the laboratory. The dynamic loading caused by the drilling action may therefore be more severe in cast iron than in Franciscan Graywacke.

Based on the field test results, the materials selected for the experimental bits improved roller wear by 200 percent, friction-pin wear by 150 percent, and lug wear by 150 percent. Of the two experimental types, the M-50 bushing system experienced slightly less wear than the tungsten carbide bushing system. The former is therefore preferable for reasons of cost, and the fact that it utilizes the conventional hard-facing alloy on the friction pin.

* The cast iron tended to drill over-gage, thereby eliminating cone support or in-thrust.

Figure 4. Wear data for bits tested in the Drilling Research Laboratory.

Figure 5. Wear data for bits tested at Geysers, California.

Drilling Performance

The principal failure mode for conventional bits at the Geysers was excessive gage wear (see Figure 6). An analysis of resistance to gage wear incurred by reaming and drilling was therefore made. A means of combining the reaming and drilling gage wear was derived^{8, 9} by graphic interpretation of the reaming time, drilling time, and gage loss measurement (Figure 7). The slopes of the "zones of constant bit gage loss" establish the equivalency between reaming and drilling. The two can then be combined into "equivalent wear time", as shown in Equation 1:

$$H_{BIT} = H_D + 3.2 H_R \quad (1)$$

where,

H_{BIT} = hours of equivalent wear time for bit

H_D = drilling hours

H_R = reaming hours

Bit gage loss was then plotted as a function of the equivalent wear time, using Equation 1. (Figure 8).

The economic break-even point employed at the Geysers (based on experience with conventional bits) results in an average bit gage loss of 5.0 mm (0.20 inches). Figure 8 indicates that the experimental bits provided a five-hour increase in equivalent wear time. Using an average trip consisting of three hours of reaming (9.6 hours of equivalent wear) and 17 hours of drilling, the additional five hours represents an increase of 30 percent in usable hole drilled.

The amount of hole drilled to full gage by the experimental and conventional bits was also analyzed. The depth at which a bit became under-gage

Figure 6.
Shirttail area of a
conventional bit, showing
excessive gage wear.

Figure 7. Bit gage loss as a function of reaming time and drilling time.

Figure 8. Bit gage loss as a function of equivalent wear time.

was determined by locating the depth at which the next bit began reaming. Table II compares reaming time, total drilling time, total distance drilled, in-gage drilling time, distance drilled in-gage, and equivalent wear time for the experimental bits and some of the comparative bits. Bits used only for reaming were not included in this analysis.

Although the distances drilled in-gage could be compared directly, drilling time is a more accurate criterion since it tends to normalize differences in formation drillability. The experimental bits drilled an average of 11.5 hours, as opposed to 6.8 hours for the conventional bits, yielding a 70 percent improvement. The discrepancy between this figure and the 30 percent increase in usable hole per bit results from the economic break-even point used. The high cost of the time lost in tripping dictates drilling substantially beyond the point where the bit goes under-gage. Thus, while the break-even

point can be reoptimized for the experimental bits to improve upon the 30 percent value, the 70 percent improvement figure represents an upper bound on what can be expected.

TABLE II
IN-GAGE REAMING AND DRILLING

TRIP No.	BIT TYPE	HOURS REAMED	TOTAL HOURS DRILLED ¹	TOTAL DISTANCE DRILLED Meters (Feet)	HOURS DRILLED IN-GAGE	DISTANCE DRILLED IN-GAGE Meters (Feet)	EQUIVALENT IN-GAGE WEAR TIME ² (HOURS)
16	TT-1, Experimental, WC Bushing	3.3	27.3	209.7 (688)	19.3	148.1 (486)	29.9
19	TT-2, Experimental, MC-50 Bushing	1.5	16.8	76.2 (250)	0	0	4.8
24	TT-3, Experimental, WC Bushing	1.3	18.5	61.9 (203)	18.5	61.9 (203)	22.7
26	TT-4, Experimental, M-50 Bushing	5.3	18.3	87.8 (288)	15.8	75.9 (249)	32.8
43	TT-5, Experimental, M-50 Bushing	4.0	19.0	96.3 (316)	12.8	64.9 (213)	25.6
45	TT-6, Experimental, WC Bushing	1.8	13.0	57.3 (188)	2.5	11.0 (36)	8.3
AVERAGE		2.8	18.8 ³	98.1 (322)	11.5	60.4 (198)	20.7
17	R-1, Conventional, Y73-JA	2.5	26.0	164.0 (538)	2.5	15.9 (52)	10.5
25	R-3, Conventional, Y73-JA	1.5	19.8	57.9 (190)	10.8	31.7 (104)	15.6
27	R-4, Conventional, Y73-JA	3.3	18.0	107.3 (352)	14.0	84.7 (278)	24.6
44	R-6, Conventional, Y73-JA	4.0	13.5	58.2 (191)	0	0	12.8
AVERAGE		2.8	19.3 ⁴	96.9 (318)	6.8	33.2 (109)	15.9

¹ Does not include reaming

² $H_{BIT} = 3.2 H_R + H_D$

³ Penetration rate average of 5.21 m/hr (17.1 ft/hr)

⁴ Penetration rate average of 5.03 m/hr (16.5 ft/hr)

Reamer Performance

Several additional analyses were also conducted which considered the relative performance of the entire bottom-hole assembly (bit, two blade stabilizers, and one 3-point reamer) as a system. These were not included since they indicated that the reamers and stabilizers contributed very little to maintenance of the hole gage.*

Improvements in the gagewear resistance of the three-point reamers and blade stabilizers would lower Geysers drilling costs in two ways:

- Improving stabilization of the bottom-hole assembly permits higher weight-on-bit, and corresponding increased penetration rate, where undesirable inclination or deviation of the hole are present or when penetrating at an oblique angle to the formation. This savings could be at least partially realized using conventional bits, since the maximum permissible weight-on-bit, though higher than current practice, would frequently fall below the maximum advisable weight for conventional bits, 133 KN (30,000 pounds).
- Improving maintenance of hole gage permits more drilling per trip. Under these circumstances the full potential of the experimental bits can be achieved.

The materials technology used in the experimental bits are directly applicable to the three-point reamers. It may therefore be possible to realize further cost savings by constructing reaming cylinders from the steel and tungsten carbide used in the experimental bits.

* On several of the trips, the reamers and stabilizers were more under-gage than the bit.

CONCLUSIONS

Eight experimental roller-cone bits fabricated from high-temperature alloys, and utilizing more abrasion-resistant drilling inserts, were run in back-to-back drilling tests with conventional bits in the laboratory, and at the Geysers (California) geothermal field. The bits were fabricated on existing factory tooling normally used to produce conventional bits. Only minor changes in procedures and heat treating were required.

Summary conclusions are:

1. The experimental bits provided a 30 percent increase in hole drilled per bit, using standard drilling practice. The experimental bits also drilled 70 percent more in-gage hole per bit, indicating that the total amount of hole per bit can be further increased by optimizing Geysers drilling practice for the experimental bits. The failure mode was excessive gage wear.
2. Bearing life was improved by a factor of 150-200 percent in the experimental bits, indicating that higher weight-on-bit (therefore, penetration rate), longer life, and the drilling of hotter formations are possible with these bits.
3. While the economic benefit to the Geysers drilling application is direct and substantial (approximately 12 percent),⁹ the experimental bits will provide significantly higher reductions in cost-per-foot and time-to-completion as more severe geothermal drilling conditions, particularly higher reservoir temperatures, are encountered.
4. The favorable field test results indicate that commercial production

of improved geothermal bits, utilizing some or all of these materials may now be economically viable for the bit manufacturers since no tooling cost will be involved.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Clifton Carwile of the Department of Energy, Division of Geothermal Energy, and Samuel Varnado of Sandia Laboratories for their support.

The Reed Rock Bit Company fabricated a total of sixteen experimental bits on a no-cost basis, utilizing production-line facilities at a time when they were needed to meet demands for conventional bits. Dewey Thiessen and his staff, Bill Schumacher, Terry Mayo, Harry Mauzy, and John Childres ably assisted in planning, definition of process procedures, and bit fabrication.

Union Geothermal Division of Union Oil Company provided the field test site and drilling rig time at their Geysers drilling operations. Don Ash, Bob Rardin, Chuck Ward, and Alan Inman assisted in planning and coordinating the tests. Loffland Brothers, Incorporated, conducted the drilling. The authors wish to thank Bill Loffland and C. E. Reams for their assistance in controlling test conditions and obtaining survey data.

Sandia Laboratories' Drilling Technology Division assisted in the interpretation of the well log data. Alexander Maish and Joseph Polito, Jr. developed the equivalent wear relationships for reaming and drilling. Leonard E. Baker assisted with coordination and monitoring of the field tests.

The Drilling Research Laboratory personnel, under the direction of Alan Black, conducted over 100 hours of continuous drilling. Bill Leslie of the Materials and Metallurgical Engineering Department at the University of Michigan conducted the search for high-temperature steels, and assisted in the final selection of materials and heat-treating procedures for the experimental bits.

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