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FIELD DRILLING TESTS ON IMPROVED GEOTHERMAL UNSEALED ROLLER-CONE BITS: FINAL REPORT

MASTER

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Energy under Contract DE-AC04-76DP00789

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Work performed under Sandia Laboratories Contract No. 13-0226 for the U. S. Department of Energy, Division of Geothermal Energy

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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 Childers ably assisted in planning, definition of process procedures, and bit fabrication.

Union Geothermal Division of Union Oil Company provided the field test site and drill rig time at their Geysers drilling operations, and the conventional bits. Don Ash, Bob Rardin, Chuck Ward and Alan Inman assisted in planning and coordinating the tests. Loffland Brothers, Incorporated, conducted the actual 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 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.

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 selections of materials and heat-treating procedures for the experimental bits.

ABSTRACT

This report describes the development and field testing of a 222 mm (8-3/4 inch) unsealed, insert type, medium hard formation, high-temperature bit under DOE/Sandia Contract No. 13-0226, "Research to Support Development of Improved Geothermal Rolling Cutter Drill Bits". Increased performance was gained 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.

Six of the experimental bits were subjected to air drilling at 240°C (460°F) in Franciscan graywacke at the Geysers (California). Performances compared directly to conventional bits indicate that in-gage drilling time 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 drilled, compared with the conventional bits. The materials selected improved roller wear by 200 percent, friction per wear by 150 percent, and lug wear by 150 percent. These tests indicate a potential well cost savings 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 experimental bits, and Union Geothermal Division of Union Oil Company, Inc., which provided the field drilling site, and drill rig time.

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INTRODUCTION

The goal of this program is to reduce geothermal well costs, particularly for the more difficult geothermal sites, by accelerating commercialization of improved geothermal unsealed roller-cone bits. Conventional rock bits provide only 25-50 percent of their normal life when used in the more severe geothermal environments, due to the effects of elevated temperatures upon the roller, ball, and friction bearing systems. Some of the more problematic geothermal drilling sites, such as the Geysers in California, have hard, abrasive strata in the present of bottom-hole temperatures in excess of 200°C (392°F). These more abrasive formations cause accelerated wearing of the gage-row drilling inserts as well as the above-mentioned bearing problems.

The U.S. Department of Energy, Division of Geothermal Energy(DOE-DGE), therefore initiated a program to improve the temperature capabilities and resistance to gage-wear of unsealed rock bits. Terra Tek was funded, under the direction of Sandia Laboratories, for a three-year program to investigate alternative materials of construction through a program of materials property tests, and the construction and evaluation of three generations of experimental bits. Full-scale laboratory drilling tests were conducted under simulated hydrothermal drilling conditions at 316°C-600°F (first two generations) and under simulated air drilling conditions at 250°C (482°F) for the final generation. The field tests reported herein are the culmination of these efforts. Previous publications under this program are listed in references 1-18.

The Reed Rock Bit Company, Incorporated, fabricated the six experimental bits used for the field tests, as well as ten previous experimental bits, on a no-cost basis. Terra Tek directed the field testing of the bits at Union

Geothermal's Geysers drilling operations, with assistance by Sandia Laboratories. Union Geothermal provided the test site, drill rig time, and the eleven conventional Y73 JA bits on a no-cost basis. Terra Tek performed the bearing wear analysis; Sandia Laboratories assisted in interpreting the well log data.

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 the manufacture of bits from alternative materials, provided these can be forged, heat treated, carburized and machined in the normal manner. 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. Materials substitutions were with metals capable of sustaining required levels of hardness and toughness at elevated temperatures.

The experimental bit material selections are detailed in Figure 1 and Table I. The materials property requirements were derived from the results of laboratory drilling tests on two previous generations of experimental bits (see references 8, 11, and 16). The requisite materials properties for each component, and the material selected, are as follows:

1. Lugs: A carburizing bearing steel was sought for the lugs which could provide a minimum case hardness of R_c 50, a minimum core yield strength of 690 MPa (100 ksi), and a minimum fracture toughness of 100 MPa$\sqrt{m}$ (91 ksi $\sqrt{in}$) at any operating temperature to 300°C (575°F). Timken CBS-600 was selected because it could maintain a case hardness of R_c 55 and a yield strength of 1.05 GPa (152 ksi) at 300°C. Fracture toughness at 300°C was 75 MPa$\sqrt{m}$ (68 ksi$\sqrt{in}$), which was less than the design goal.

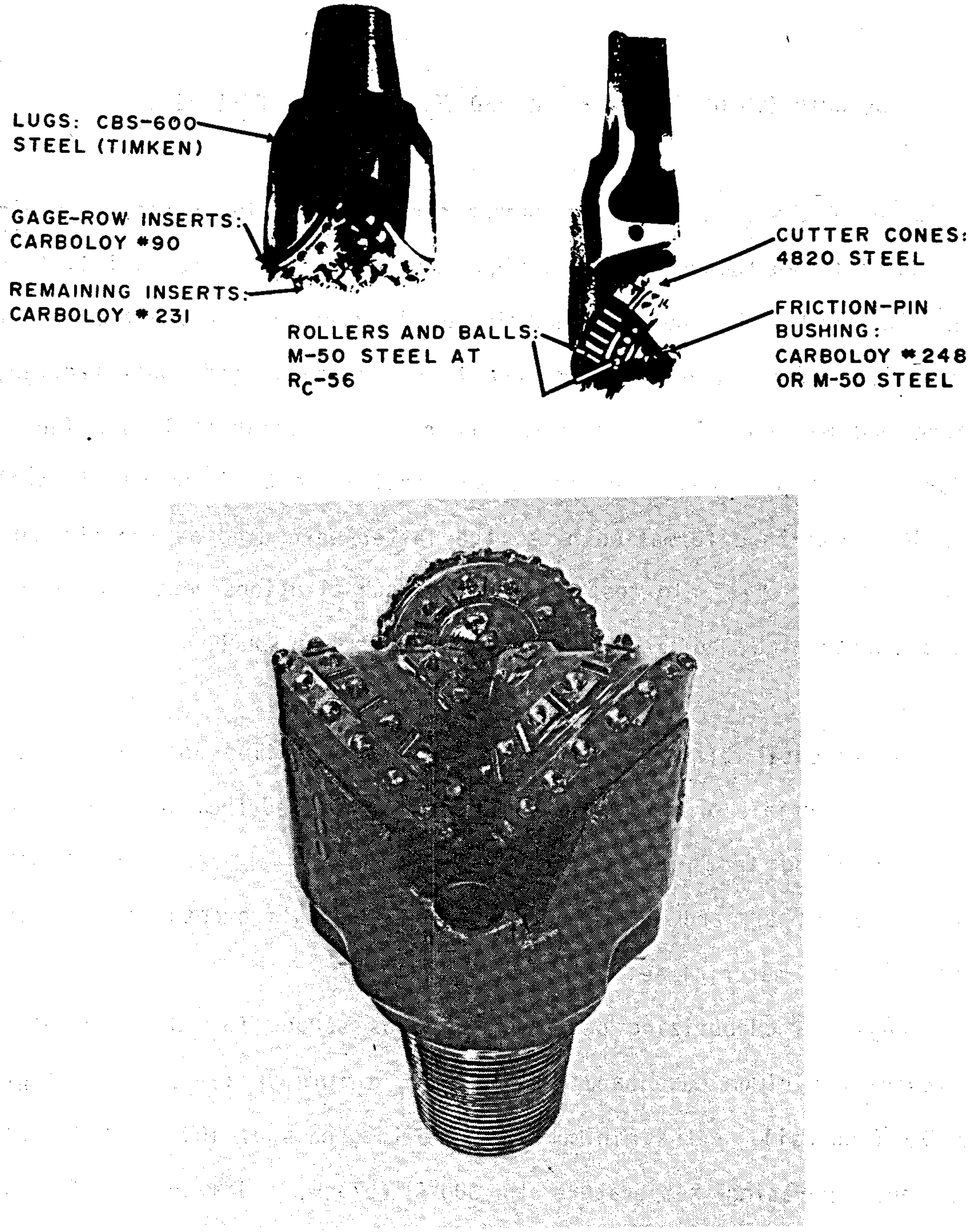

Figure 1. Materials selected for the geothermal prototype drill bits.

TABLE I

FRICTION PIN (PILOT PIN) BEARING MATERIALS

Bit Type	Materials Used For Friction Pin Bushings in Cones	Hard-Metal Alloy on Radial Surfaces of Friction Pins*
Conventional Reed Y73JA	AISI 430 Stainless Steel	Modified Cabot-Haynes Stellite no. 1. Approximate Composition: 30% Cr, 2.5% C, 1% Si, 3% Fe, 3% Ni, 12% W, 1% Other, balance Co
Experimental "M50" Type	Timken M-50 Tool Steel	Same as above
Experimental "WC" Type	General Electric/Carboloy #248 Tungsten Carbide	"Tube Metal": pulverized sintered tungsten carbide particles, 30-40 mesh size, in a Cobalt binder

*All bits utilized the Modified Cabot-Haynes Stellite No. 1 on the primary thrust surfaces (ends) of the friction pins.

The lugs of the experimental bits differed from those of the conventional bits in the shirt-tail area.* Conventional bits such as the Y73 JA utilize tungsten carbide inserts and hard-metal facing on the lug shirt-tails to reduce wear and erosion. Shirt-tail inerts were not installed in the experimental lugs due to difficulty encountered in drilling holes in the CBS-600 steel, which had a hardness of R_c40. This problem could have been avoided by drilling the holes prior to hardening (see Manufacturability section of Appendix B). All bits received the same amount of hard-metal facing on the shirt-tails.

* The shirt-tails of the bit are located on the lower portion of the lugs; the shirt-tails frequently come in contact with the hole wall and serve to stabilize the bit.

2. Cones: The steel used for bit cones should be capable of maintaining a case hardness of R_c 50, a minimum core yield strength of 1.00 GPa (150 ksi), and a minimum fracture toughness of 90 MPa$\sqrt{m}$ (82 ksi$\sqrt{in}$), to 300°C. CBS-600 was sought for this application, but due to scheduling problems at the bit manufacturing facility, conventional cones of AISI 4820 were selected. AISI 4820 can maintain a case hardness of only R_c 45 at 300°C. Friction pin bushings and thrust buttons, which are press-fit into the cones, are discussed in item No. 4, below.

3. Rollers and Balls: Rollers and balls were required to be through-hardened to at least R_c 50. A minimum core yield strength of 1.7 GPa (250 ksi) and a minimum fracture toughness of 20 MPa$\sqrt{m}$ (18 ksi$\sqrt{in}$) at temperatures to 300°C were also required. AISI M-50 tool steel with a reduced hardness of R_c 56 was selected because it could provide levels of hardness, strength and toughness approximately equal to the requirements.

4. Friction Pin Bearings: The friction pin bearing system consists of a bushing and a thrust "button" which are press-fit into the cone, and "hard metal" alloy(s) which is/are applied to the end and outer diameter of the lug friction pin. The system must be capable of withstanding temperatures (induced by friction and the bottom hole temperature) of 600°C (1110°F), with stress on the order of 35-70 MPa (5,000 - 10,000 psi).

Two experimental systems were selected, and four experimental bits of each type were constructed. One utilized full-hard (R_c 64) AISI M-50 tool steel bushings and conventional "hard metal"; the other utilized General Electric Carboloy No. 248 tungsten carbide bushings and a "tube metal" on the lugs (see Table I). The hardness of M-50 is R_c 52 at 550°C (1022°F) and R_c 45 at 600°C (1110°F). Data were not available on the hardness at temperature for the Carboloy No. 248, Stellite No. 1, nor the "tube metal"; the hardness level of these materials is expected to be relatively unaffected by temperatures to 600°C (1110°F). All bits utilized conventional AISI M2 tool steel thrust buttons, and the standard Stellite No. 1 on the ends of the friction pins.

5. Gage Row Inserts: Tungsten carbide inserts with greater resistance to abrasive wear were required to prevent the excessive loss of gage diameter experienced in hard, abrasive formations. A minimum fracture toughness of 12 $MPa\sqrt{m}$ at temperatures to 300°C was required. This was determined by conducting a series of fracture toughness tests on the conventional grade (General Electric Carboloy 231) at temperatures to 300°C. Similar tests were then performed on candidate grades known to possess improved abrasion resistance; these tests are presented in Appendix B. Carboloy grade 90 was selected because it met the toughness specification and provided a 75% improvement in wear resistance. According to the manufacturer, grade 231 has a wear number* of 4 cc^{-1} and a hardness range of R_A 87.4 to 88.2. Grade 90 has a wear number of 7 cc^{-1}, and a hardness range of R_A 88.8 to 89.3

A detailed review of the materials and heat treat specifications outlined above is presented in Appendix B. Results of laboratory materials property tests conducted at temperature are also presented for these materials.

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* The ANSI/ASTM B611-76 "Standard Test Method for Abrasive Wear Resistance of Cemented Carbides" was used by Carboloy for these tests; this method was formerly known as the "Riley Stoker Test". The "wear numbers" shown above are higher for improved resistance to wear. Carboloy refers to these values as "Wear Resistance"; although this term is more descriptive, it contradicts the terminology used in ANSI/ASTM B611-76.

GEYSERS DRILLING CONDITIONS

Arrangements were made with Union Geothermal, Inc., of Santa Rosa, California, for field-testing of six experimental bits, and at least six conventional bits for comparison. The tests were conducted at the Geysers, California, with Loffland Brothers, Inc., as drill rig operators.

The Geysers drilling conditions provided an ideal test site, since all factors known to adversely affect bit life were present.[19]* The specific Geysers drilling conditions which shorten bit life and reduce penetration rate, in order of imporantance, are:

1. Air drilling at Formation Temperatures - The drilling air attains the formation temperature of 240°C by the time it reaches the bit. Drilling with air provides less cooling to the friction pin, roller bearings and ball bearings than is provided by mud or water.** The lower rate of heat transfer provided by air results in excessive localized frictional heating at points of contact, particularly the friction pin.

   At least two important geothermal drilling situations require that air be used as the circulating fluid:

   (1) Subhydrostatic hydrothermal or steam reservoirs where mud might permanently plug productive zones, or quench steam vents; and

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* It should be noted that although hydrogen sulfide gas and corrosive salts were not present in significant amounts, these are not considered significant to bit life. This subject is discussed in detail in Appendix B, Subappendix B.

** In unsealed bits, a fraction of the drilling fluid is discharged through the bearings to provide cooling and prevent detritus from entering.

(2) Exploration drilling where the cooling effect of mud or water would obscure the actual formation temperature, such as the "Hot Dry Rock" resources.

2. Hard Formations - The hard formations such as Granodiorite and Chert require high weight-on-bit 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 cutting structure which is generally most pronounced on the outermost rows of inserts, resulting in premature loss of "gage".

4. Low Weight-On-Bit - The use of low weight-on-bit results in accelerated gage-wear and a resulting decrease in the amount of in-gage hole obtained from the bit; this effect will be discussed in greater detail later in the report. Two situations that require reduced bit weights are: the crossing of inclined faults or dips; and the drilling of deviated (non-vertical) holes with worn stabilizers and reamers.

   When inclined faults or dips are encountered, the bottom-hole assembly tends to follow the fault unless the weight-on-bit is reduced.

   Holes are often deviated in order to reach several parts of the reservoir from a common well site. The amount of deviation can increase uncontrollably if the stabilizers and reamers are worn*, and bit weight must be reduced to maintain the desired angle.[20]

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* Gravity causes sagging of the drill collars, which gives the bit an unwanted upward orientation; the weight-on-bit accentuates this effect. Stabilizers and reamers help to prevent this, but as they become worn, sagging of the collars occurs.

5. "Open-Fracture" Formations - Drilling in "Open Fracture" Formations causes impact loading as the bit drops into fractures, or when rolling over large, loose fragments. Cones, rollers, balls, inserts and lugs can be broken, destroying the bit and necessitating the "fishing" of parts from the well.

6. Swelling - Swelling of a previously drilled hole requires reaming, resulting in wear on the gage cutters and ball bearings.

DRILLING TEST PROCEDURES

Field testing took place at Union Geothermal's CMHC #6 well in August and September, 1978. Six experimental bits and eight conventional Reed Y73 JA bits were evaluated. The test conditions and procedures are summarized in Table II, and described in greater detail below.

TABLE II

WELL INFORMATION FOR CMHC #6 WELL

AIR FLOW	1.1 $m^3 s^{-1}$ (2,400 CFM) = 1.50 Kg s^{-1} (12,000 lbs/hr)
UNISTEAM[R] DILUTION	84:1 volumetric (1/3 gal/barrel)
SOLUTION INJECTION RATE	0.063 ℓ s^{-1} (1 GPM) = 0.063 Kgs^{-1} (500 lbs/hr)
UNISTEAM[R] USED PER HOUR	2.7 Kg (6 lbs)
WEIGHT RATIO OF UNISTEAM[R]/AIR	1/1,900
WEIGHT RATIO OF SOLUTION/AIR	1/23
RATIO OF HEAT CAPACITIES OF SOLUTION* TO AIR (PER HOUR PER DEGREE C)	130 Kcal/1,300 Kcal = 0.10

*1.38 MPa (200 psi), 246°C (475°F); water/Unisteam[R] in vapor phase upon arrival at drill bit.

1. Conventional mud drilling was used to drill to slightly above the reservoir, 1,680 m (5,500 feet), at which point the well was cased and cemented. A downhole mud motor was then used to deviate the hole to the required inclination and direction prior to commencing air drilling into the producing zone; hole inclination and direction were normal to as many faults and joints as possible. Insufficient steam flow was obtained from the first leg, and it was plugged; a new leg was initiated with the mud motor.

2. Franciscan graywacke and micro-graywacke sandstone were the predominant reservoir rock. Owing to the unique combination of abrasiveness (quartzite and feldspar phenocrysts), strength, and ductility, this formation represented a worst-case gage-wear situation, geothermal or otherwise. *

3. Air flow was a consistent 1.1 m^3s^{-1} (2400 CFM) when drilling the reservoir. Survey data indicated that all drilling was done at a bottom-hole temperature between 204°C and 247°C (400 - 477°F), with the exception of the first nine hours on the first experimental bit, which started at about 120°C (250°F). Well entry pressure was initially 1.38 - 1.52 MPa (200 - 220 psi), rising to 3.45 MPa (500 psi) at full steam production. A mixture of water and Unisteam[R] (Union Oil Co., Inc.) was injected into the air stream (Table III). This was done primarily to reduce drill pipe and casing wear and corrosion by coating detritus with an amine; Unisteam[R] also contains corrosion inhibitors. Drillers and the bit manufacturers feel that the Unisteam[R] is not significant to bit life.

The experimental bits were run with 19 mm (0.75 inch) air nozzle openings**, whereas the conventional bits were inadvertently run without nozzles, resulting in 29 mm (1.14 inch) nozzle openings. Airflow through the bearings is proportional to the pressure drop across the nozzles. The experimental bits therefore had a total

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* Mining ores such as taconite are noted for excessive gage-wear but blastholes are shallow and gage-wear maintenance is not important.

** The experimental bits did not have nozzle sockets due to difficulties encountered in machining (see Manufacturability section of Appendix B). The bits had 19 mm (0.75 inch) holes bored at the nozzle socket sites.

airflow through the bearings of 0.32 m^3s^{-1} (680 CFM) while the conventional bits received 0.17 M^3s^{-1} (350 CFM). Although this difference in test conditions was undersirable, Union Geothermal personnel believed that it would not affect bearing wear, based on previous testing. Union Geothermal had run comparison tests on conventional bits fitted with nozzles as small as 12.7 mm (0.500 inch), as well as 16 mm (0.63 inch), 19 mm (0.75 inch), and 29 mm (1.14 inch); no noticeable differences in bearing life were observed.[26] The larger openings are favored by the drillers because lower pumping pressure is required.

4. All experimental bits and conventional bits used in the analyses drilled at 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. It should be noted that although bit weights as light as 45 KN (10,000 pounds) are frequently necessitated at the Geysers, these were avoided for the test program.

5. There were no precise indicators of bit condition - the drilling superintendent therefore based his decision to pull a bit from the hole on the estimated amount of gage loss. This estimate was based on the hours of reaming, hours of drilling, penetration rate, weight-on-bit, RPM, and formation drillability.

6. Hole gage loss was permitted to be no greater than 6.4 mm (0.25 inch), although 5.1 mm (0.20 inch) was typical. It should be noted that bit manufacturers recommend that bits be subjected to no more than 3.0 mm (0.13-inch) of reaming prior to drilling. However, the

TABLE III

GEYSERS AIR MAKEUP

Location	Big Geysers Field, Cobb Mountain Hunt Club, Sonoma County, California, Well #6, Site #12
Driller	Loffland Brothers, Inc., Rig #50
Formation	Franciscan graywacke and micro graywacke
Depth	1800-2600 m (6000-8500 feet)
Formation Temperature	190-245°C (375-475°F)
Weight on Bit	89-156 KN (20-35,000 pounds)
Rotary Speed	40-70 (60 typical) RPM
Deviation	10° - 15° first leg 18° - 19° second leg
Drilling Fluid	1.1 m^3s^{-1} (2400 CFM) Air/Unistream[R]

conditions present at the Geysers apparently required exceeding this guideline. Reaming undergage hole in Franciscan graywacke caused excessive wear on the gage-row inserts and the ball-bearing systems. The bits were generally worn undergage upon completion of reaming and hence drilled all undergaged hole. A "vicious circle" of undergage hole and gage-worn bits existed.

7. Rotary speeds ranged between 40 and 70 RPM when drilling the reservoir rock, but most drilling was done at between 55 and 65 RPM.
8. 222 mm (8-3/4 inch) hole was standard throughout the reservoir.
9. The bottom-hole assembly (BHA), detailed in Table IV, used standard oil-field hardware to stabilize the drilling string and ream the hole to 222 mm (8-3/4 inch).

TABLE IV

BOTTOM-HOLE ASSEMBLY FOR GEYSERS AIR DRILLING (TOP TO BOTTOM)

TOOL	QUANTITY
Drill Collar, 152 mm dia X 9.14 m (6" X 30')	9
Stabilizer, blade-type, 222 mm dia X 1.22 m (8-3/4" X 4')	1
Drill Collar, 152 mm dia X 9.14 m (6" X 30')	1
Stabilizer, blade-type, 222 mm dia X 1.22 m (8-3/4" X 4')	1
Monel Drill Collar, 152 mm dia X 1.52 m (6" X 30')	1
Reamer*, roller-type, 222 mm dia X 1.52 m (8-3/4" X 5')	1
Drill Bit, 222 mm (8-3/4")	-
OVERALL LENGTH	105 m (344')

*The full name of this device is "three-point reaming stabilizer" but it is commonly referred to as a "three-point reamer".

Six experimental bits and eight Reed Y73 JA conventional bits were run as part of the test program at the Geysers. Since Union Geothermal routinely drills with Reed Y73 JA bits, the comparative bits represented current practice for Geysers drilling, in addition to being geometrically identical to the experimental bits. The two types of experimental bits (see Table I), and the conventional bits were run alternately in order to minimize the influence of drilling test conditions variation. Figures 2 and 3 illustrate reaming distance, drilling distance and gage loss for each bit used in either Leg #1 or Leg #2 of well CMHC #6. Additional data, including RPM, penetration rate,

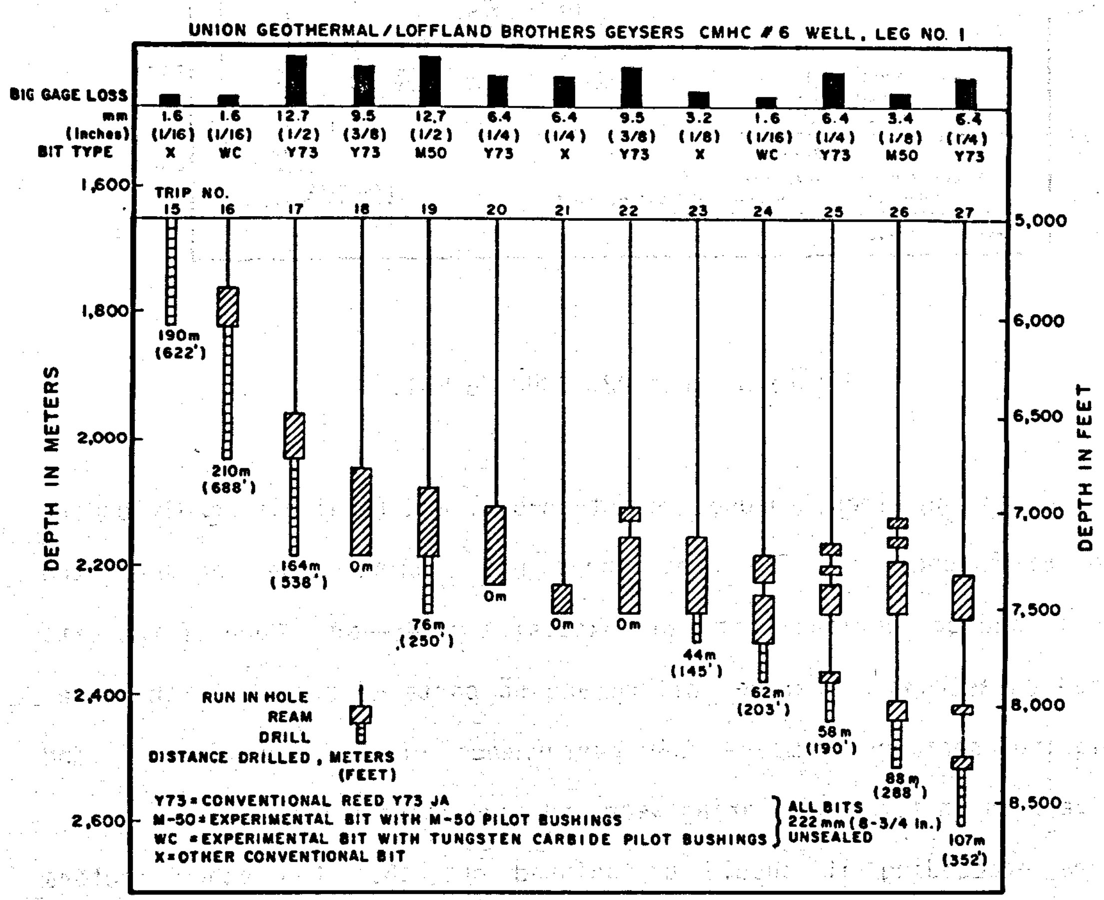

Figure 2. Let #1, CMHC #6 Well

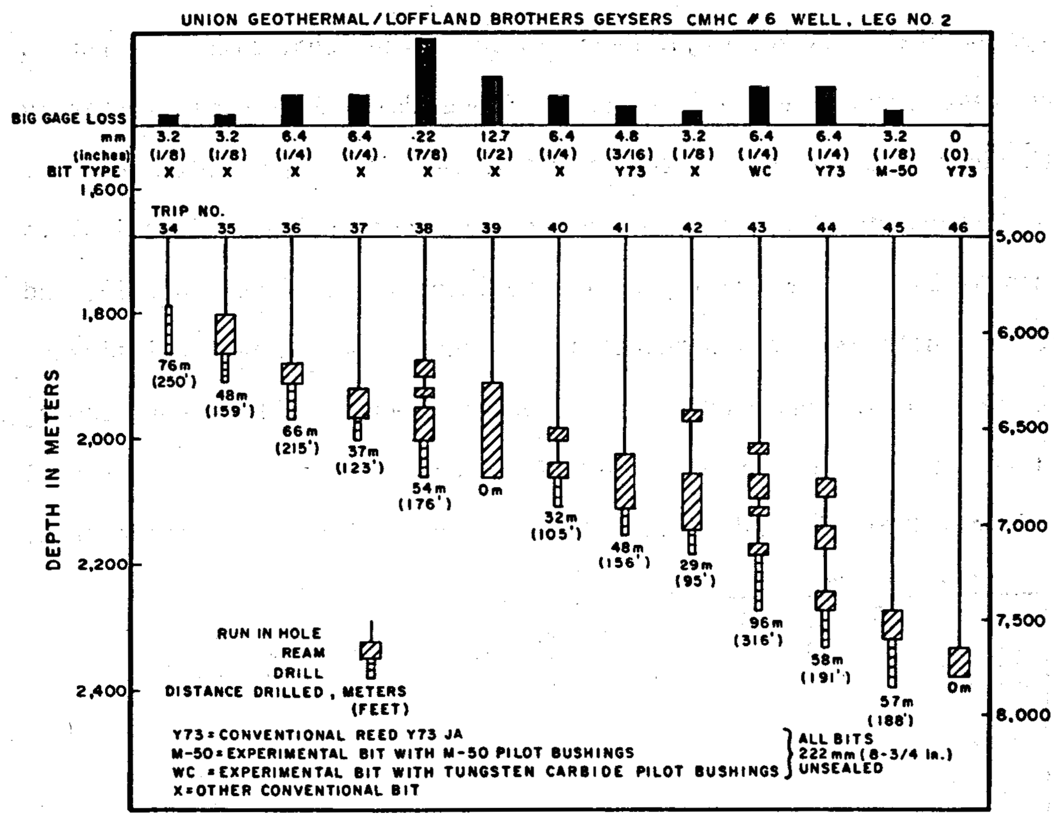

Figure 3. Let #2, CMHC #6 Well

drilling and reaming times, torque, weight-on-bit, and final bit condition are presented in Appendix A. The predominant bit failure mode for both the experimental and conventional bits was excessive gage-wear. None of the bits experienced catastrophic bearing failure and no parts were lost in the hole. The following sections compare the performance of the experimental and comparative bits in terms of bearing wear and gage maintenance.

Before proceeding it should be pointed out that two other factors contributed to the reaming problem:

1. Formation swelling. This is evidenced by the recurring requirements for reaming in the 2,130 - 2,290 meter (7,000 to 7,500 foot) level of Leg #1 (Figure 2) and 1,980 - 2,130 meter (6,500 to 7,000 foot) level of Leg #2 (Figure 3). This swelling constituted a significant part of the Geyser reaming problem. Bits run predominantly to ream out formation swelling - trips 18, 20, 21, 22, 23 and 39 - were not analyzed for wear.
2. Undergage Bottom-Hole-Assembly (BHA). The three-point reamers and blade stabilizers generally wore out of gage by a greater amount than the bit. This undergage condition of the bottom-hole-assembly further increased gage-wear by permitting eccentric running of the bit and by requiring the use of lighter weight-on-bit to maintain directional stability when crossing faults or when attempting to decrease hole inclination. Lighter weight-on-bit required more revolutions to drill a given distance and, hence, additional gage-wear. The relationship between the performance of the bottom-hole assembly and the drilling test results are discussed in the "Conclusions" section.

Drilling Performance Analysis

The overall performance of any rock bit is generally characterized in two ways:

- Penetration rate
- Amount of usable hole drilled in a given formation

Since the experimental bits were geometrically identical to the conventional bits, no difference in penetration rate can be expected, unless higher bit weighting is employed. Higher bit weighting was therefore sought for the experimental bits in order to fully utilize the improved bearings* to obtain a higher penetration rate and increased drilling distance per bit. Unfortunately, Geysers drilling practice often required that weight-on-bit be reduced to correct the inclination or deviation of the bottom-hole assembly, as explained previously. Since the quantity of experimental bits was limited, obtaining a sufficient number of uniform, high-weight tests was unlikely. The experimental bits and comparative bits were therefore run at normal bit weights using standard drilling practice; no differences in penetration rate were observed.

The amount of usable (in-gage) hole drilled per bit can therefore be used as a basis of comparison for the experimental and comparative bits. In Geysers drilling, the amount of usable hole is a function of four important factors:

- The formation drillability
- The ability of the bit to resist gage-wear
- The ability of the stabilizers and reamers to resist gage-wear
- The economic break-even point used by the driller

The only readily available data for characterization of the formation drillability was the rate of penetration. However, the footage drilled and the rate of penetration are both taken into account if bits are compared on the basis of drilling time. Since the penetration rate varied from 3.1 m (10 feet) per hour to 7.6 m (25 feet) per hour for these tests, drilling time was utilized in the analyses.

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* The superior bearing performance of the experimental bits, discussed previously, had already been established through laboratory drilling tests (see Appendix B and reference 25).

In Geysers drilling, the economic break-even point, i.e., the time at which the drilling superintendent terminates down hole drilling, is determined by (estimated) gage loss of the hole.* This is generally held to 5.1 mm (0.20 inch), as determined by measurement of the stabilizers, reamers and bit when they are removed from the hole. The hole gage is not surveyed, nor is it possible to determine hole gage (and therefore the condition of the bit) while drilling. The drilling time varies somewhat for each trip, depending upon hours of reaming, weight-on-bit, penetration rate (formation drillability), and drilling time; the decision to terminate the trip is based solely on the drilling superintendent's experience with these parameters. Since there had been no prior drilling experience with the experimental bits, they were subjected to the same break-even point analysis as the conventional bits (i.e., total drilling and reaming times were roughly equivalent). It will be shown that the experimental bits permit more drilling per bit and hence require a different break-even point than conventional bits.

It can be seen that relative bit performance had to be determined from the condition of the bottom-hole assembly and the amount of reaming and drilling done. In addition, the bit performance had to be separated from the overall performance of the bottom-hole assembly. Bit performance was therefore analyzed in two ways: as a function of bit gage loss, and as a function of hole gage loss. The bit gage loss analysis yielded a direct assessment of the ability of the bit to resist gage-wear. The hole gage loss analysis evaluated bit performance in conjunction with the specific reaming and stabilizing hardware (bottom-hole assembly) used at the Geysers.

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* In oil and gas drilling, which generally involves softer, less abrasive formations, bearing wear or cutting structure wear is the factor limiting bit life.

Bit Gage-Wear Analysis - The hole diameter (gage) is maintained by the outermost row of drilling inserts on each of the cones. Gage-wear was measured by placing a ring having an inner diameter of 222 mm (8 3/4 inch) in contact with the gage rows on two cones, and measuring the clearance between the ring and the gage inserts on the third cone. The gage-wear values used in the report are two-thirds of the ring-gage measurement, as is standard practice.

The lug shirt-tail areas act as a stabilizer for the bit, and do not contribute significantly to maintenance of hole gage. The diametral wear of the lug shirt-tails was therefore not used in analyzing bit performance. No differences were noted in shirt-tail wear, despite the fact that the experimental bits did not have tungsten carbide inserts, as described previously.

Evaluation of the relative performance of the bits required a means of combining the wear caused by reaming with that caused by drilling. The former is particularly important because of the large, and substantially different amounts of reaming required on each trip. The reaming must be characterized by data available at the surface, such as time and depth. The time spent in reaming is considered to be roughly proportional to the wear induced, whereas the distance reamed is less accurate. Gage-wear on the bit, reamer, and/or stabilizers is known to be closely associated with the number of revolutions of the BHA. Since the drilling RPM was relatively constant, gage loss was considered to be proportional to drilling time. The actual relationship between gage loss and reaming time could not be defined more accurately due to the lack of intermediate wear measurement data. Drillers believe that the rate of wear increases significantly beyond 6.4 mm (.25 inches) of bit gage-wear, but no study has been made to substantiate this.

It therefore remained to establish the equivalent wear relationship between reaming time and drilling time. This derivation was accomplished by graphic interpretation of the gage-wear and well log data, and is presented in Appendix A. The equivalent wear relationship for both the experimental and conventional bits is given by Equation 1, below:

$$H_{BIT} = H_D + 3.2\ H_R \tag{1}$$

where,

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

H_D = drilling hours

H_R = reaming hours

The effect of reaming is 3.2 times more detrimental to the bit gage-cutting inserts than is drilling.

Bit gage loss is plotted as a function of equivalent wear time for the conventional and experimental bits in Figure 4. A large amount of scatter was noted for the five experimental bits*. This is probably due to differences in the abrasiveness of the formation, and there is no way to measure the abrasiveness directly. It is assumed that these differences affected both the experimental and conventional groups equally.

At a constant gage-loss of 5.0 mm (0.20 inches), which is the break-even point used at the Geysers, 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

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* The first of the six experimental bits drilled softer strata than all other bits (see Table V, Trip 16). This bit was not used in the gage-wear analysis.

** "Usable hole" is a hole less than 5.1 mm (0.20 inch) undergage, according to the break-even analysis used.

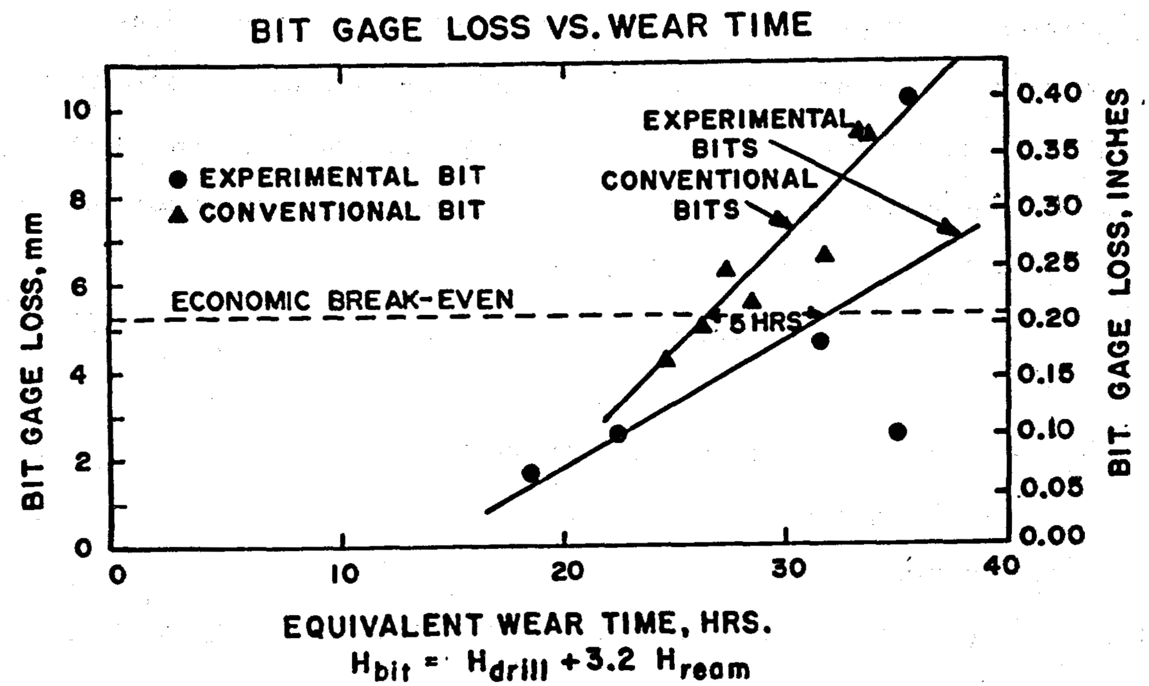

Figure 4. Bit gage loss as a function of equivalent wear time.

independent of the performance of the BHA.

In comparing the amount of in-gage hole drilled by the experimental and conventional bits, the point at which the next bit in the hole began reaming was taken to be the point at which the prior bit went undergage. This analysis, which is detailed in Appendix A, showed that the experimental types drilled an average of 70 percent more in-gage hole than the conventional bits. The discrepancy between this figure and the 30 percent increase in usable hole per bit results from the break-even point analysis. The high cost of the time lost in tripping dictates drilling substantially beyond the point where the bit goes undergage. Thus, while the break-even point can be reoptimized to improve upon the 30 percent value, the 70 percent figure represents an upper bound on what can be expected.

Bottom-Hole Assembly (BHA) Performance - This analysis compares the reaming/drilling performance of the complete bottom-hole assemblies used in conjunction with the experimental and conventional bits. It can be seen from Table V that the experimental bits were more resistant to gage-wear on three of the five trips (16, 24, 26) for which data were available, the experimental bits had less gage-wear than the other elements of the BHA. However, this was not true for any of the six runs with conventional bits for which data were available. The reamers and stabilizers tended to wear out of gage by a greater amount than the bits; this was attributed to eccentric rotation of the BHA. The procedure used to derive the equivalent wear relationship between reaming time and drilling time for the BHA's was essentially identical to that used for the bits, and is presented in Appendix A. The relationship for BHA's equipped with experimental or conventional bits is given by Equation 2, below:

$$H_{BHA} = H_D + 2.5\ H_R \quad (2)$$

where:

H_{BHA} = hours of equivalent wear time for BHA

H_D = drilling hours

H_R = reaming hours

It can be seen from Equation 2 that reaming is 2.5 times more influential than drilling in determining loss of gage diameter for the BHA (and hence hole diameter). This is somewhat less than the factor of 3.2 experienced by the bits (equation 1), since the bit is always exposed to a more severe reaming situation than is the rest of the Bottom Hole Assembly.

Figure 5 gives the BHA gage loss as a function of equivalent wear time for the BHA's fitted with conventional bits, and the BHA's fitted with experimental bits. The experimental bits provided approximately five additional hours of equivalent wear time, i.e., five hours of drilling or two

TABLE V

GAGE-WEAR OF BOTTOM-HOLE ASSEMBLIES

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)

hours of reaming, as compared to the conventional bits. This represents a 30 percent increase in usable hole drilled for the BHA's equipped with an experimental bit.

Bearing Wear Analysis

A total of twelve bits (i.e. 6 experimental and 6 conventional bits), were disassembled and measured for wear. Each lug and cone set was measured at sixteen locations; six balls and six rollers were selected at random from each lug and measured for minimum and maximum wear. These measurements were compared with measurements taken prior to final assembly of the bits at Reed

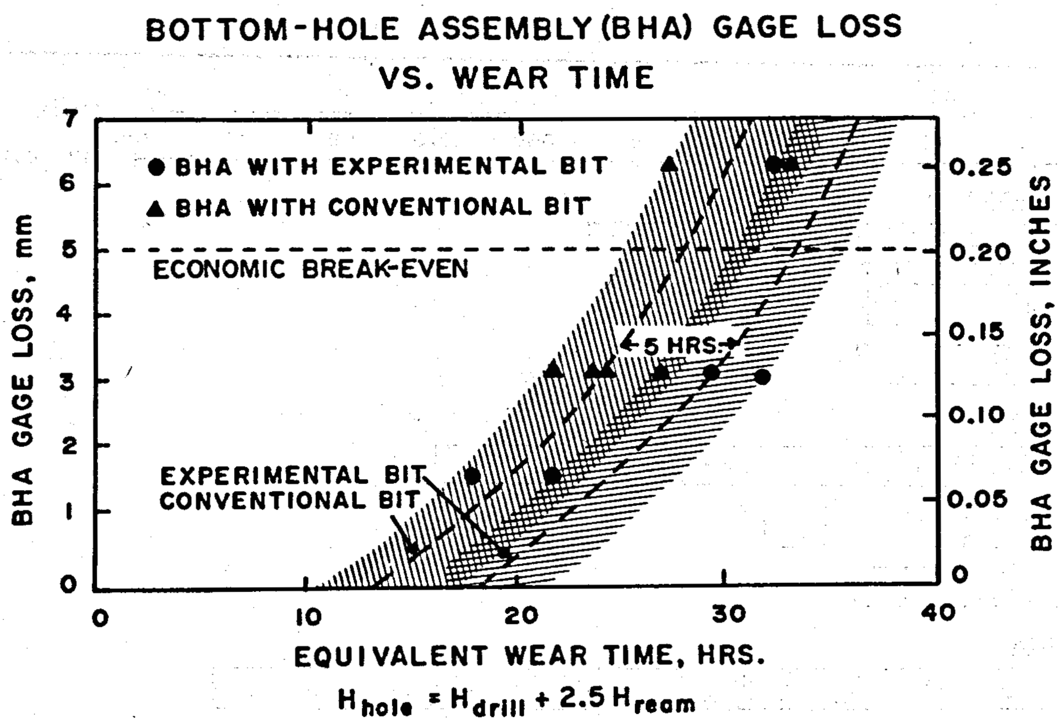

Figure 5. Bottom-hole assembly gage loss as a function of equivalent wear time.

Rock Bit Company* to determine wear; these data are presented in Appendix A. Ten of these twelve bits were used in the bearing wear analysis: the other two bits experienced excessive reaming which was atypical of good drilling practice. Figure 6 gives a composite of the total wear in each bearing system (roller bearing, ball bearing, and friction pin areas) for the conventional bits (A), experimental bits with tungsten carbide bushings (B), and the experimental bits with M-50 bushings (C). The values shown are averages for all lugs, cones, or bearings within that group. The average reaming and drilling times are nearly identical for all bits, hence direct comparisons of wear are possible.

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* Reed Rock Bit Company, Division of Baker International, was formerly known as the Reed Tool Company, Division of Baker International.

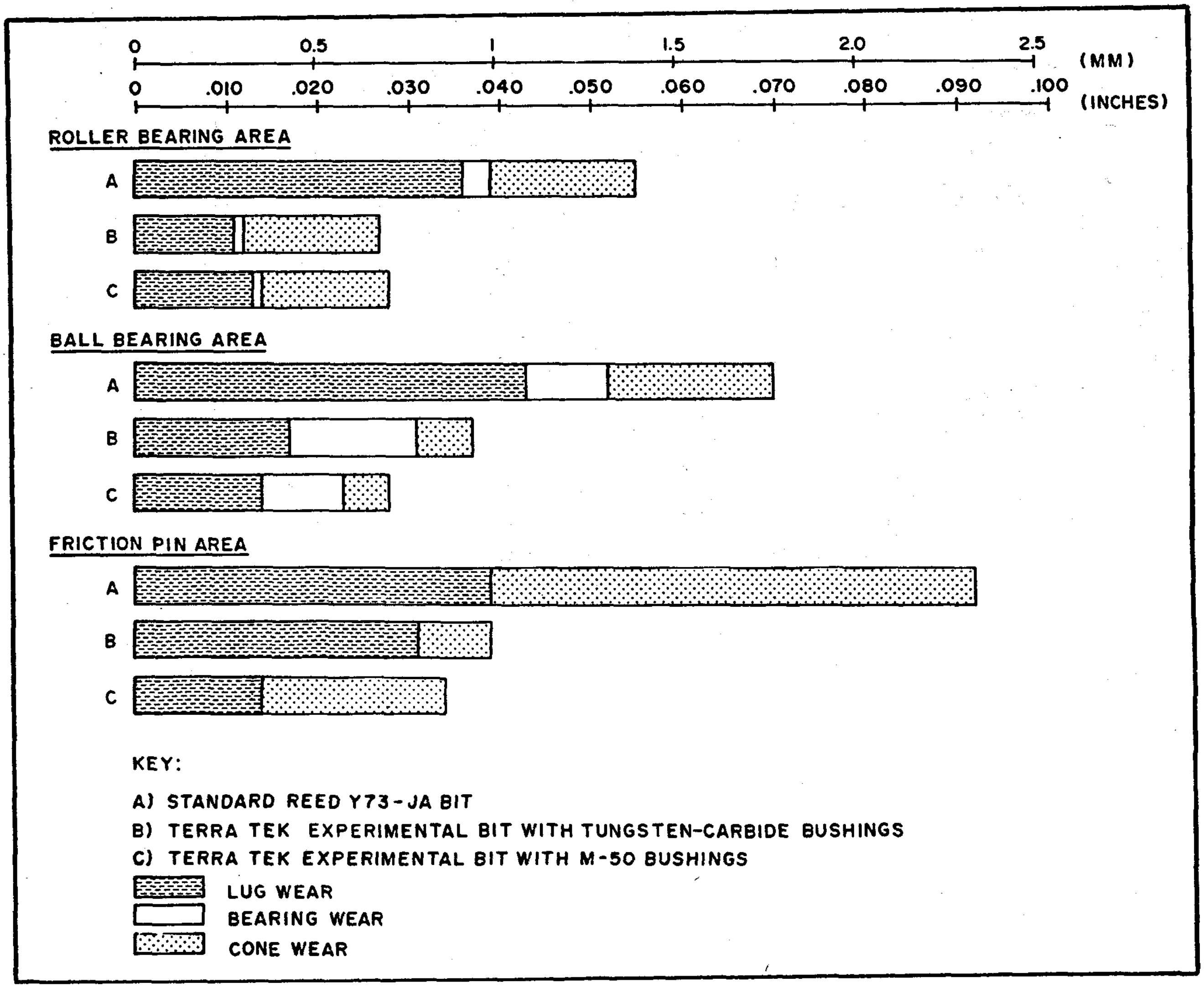

Figure 6. Wear data for bits tested at Geysers, California

The following conclusions and observations were drawn:

Lugs - The use of CBS-600 steel (Timken, Inc.) on the experimental bits reduced wear in the ball and roller races by 2.5 to 1, and also contributed to the reduction of wear in the friction pin (pilot pin) area, as compared with the wear experienced by the conventional AISI 8720 lugs. Micro-hardness traces indicated that surface temperatures exceeded 400°C on the roller and ball races, and 600°C under the hard-facing metal on the end of the friction pin. Deformation of the friction pins was noted on the experimental bits but to a lesser extent than on the Y73 JA bits.

Cones - The cone bodies of the experimental bits were standard Y73 JA cones of AISI 4820 steel, and differed only in the pilot bushings, discussed below, and the gage-row inserts, discussed under "Drilling Performance Analysis." Wear in the roller race area of the experimental bits was approximately equal to that of the Y73 JA bits. Wear of the ball races was significantly reduced in the experimental bits, but this was most likely due to a higher percentage of the thrust load being carried at the friction pin due to the poor performance of the balls (discussed below).

Rollers - The M-50 roller-bearings experienced only about 0.08 mm (0.003 inches) of wear, which is about one-third as much as on the conventional AISI S2 rollers. Wear was uniform; little measurable taper or diametral variation was noted. The M-50 rollers were heat-treated to a reduced hardness of about R_c 56 to improve toughness; wear resistance could undoubtedly be further improved by using the normal hardness of R_c 62-64, but at the risk of brittle failure under severe impact loading.

Balls - The ball bearings on all three bit types wore excessively and nonuniformly (see Appendix A). The direct cause was the excessive reaming, which utilizes reverse-loading of the ball-bearing systems to support the cones. The M-50 balls, which had been heat treated to a hardness of R_c 56, wore more than the AISI S2 balls on the conventional bits. The relatively poor performance of the M-50 balls, as compared to the M-50 rollers, and the out-of-round condition of the balls indicate that the primary ball wear mode is different than for the rollers, which experienced frictional surface wear.

One possibility is impact-fatigue and surface spalling caused by the discontinuities in the lug ball race at the air slots in the ball retainer plug (Figure 7). Unfortunately, there is little evidence to support this hypothesis, other than the fracture-toughness data for M-50 and S2 (see Appendix B), which indicates lower toughness for M-50, and hence higher susceptability to impact failure. Minor deformation was evident on the edges of the air slots, indicating that the balls were under load as they crossed the plug area. The cause of the excessive wear on the balls is uncertain and further full-scale drilling tests are needed. A steel with higher hardness and fracture toughness may be required for this application.

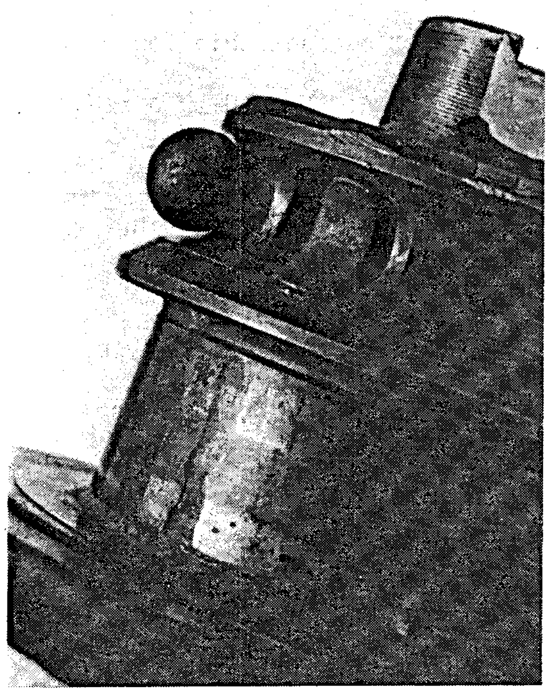

Figure 7. Ball retainer plug and ball bearing.

Friction Pin Area - The cone pilot bushing material, the lug material and the friction pin hard-facing material must be discussed collectively since they are selected as a system (see Table I). The two experimental systems each reduced the total radial wear by a factor of about 2.5 over the conventional AISI 430 stainless steel bushing/Stellite No. 1 system. The underlying CBS-600 lug material supported the hard-facing on the two experimental types better than did the conventional 8720 lug material. The experimental M-50 bushing/Stellite No. 1 system wore slightly less than the more expensive Carboloy No. 248 bushing/"tube metal" system. Additionally, two of the nine Carboloy bushings broke or disintegrated and could not be used in the wear analysis. The M-50 system is therefore preferable for reasons of cost, performance, and the fact that it uses the standard hard-facing material.

DISCUSSION

Cutting Structure Performance

It must be noted that Geysers drilling represents a worst-case gage-wear situation due to the high strength, high ductility, and extreme abrasiveness of the Franciscan graywacke sandstone. Resistance to gage-wear was substantially improved by the substitution of a harder, more abrasion-resistant (but less tough) tungsten carbide alloy on the gage row. Since these inserts wore primarily by abrasion, as opposed to breaking or spalling, it should be possible to use an even more wear-resistant, but less tough, alloy on the gage row.

For added gage-maintenance capability the following areas of development are recommended, in order of preference:

(1) The use of a more wear-resistant tungsten carbide alloy for the gage inserts.

(2) The use of more gage-row inserts.

(3) The use of polycrystalline diamond.

The first alternative appears feasible and an additional 10 percent increase in usable drilling distance is likely. It should be noted that tungsten carbide alloys have been optimized for this type of application, and the development of a substantially better alloy is unlikely in the near future.

The second alternative, the use of more inserts on the gage rows, could be accomplished by using a hard-formation bit design (Figure 8). The Y73 JA bit used in these tests (Figure 1) is a medium-hard formation bit (similar to Reed Mining Tools* M-74) which uses "pads" to increase the insert protrusion,

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* Reed Mining Tools, Inc., Mining Equipment Group of Baker International.

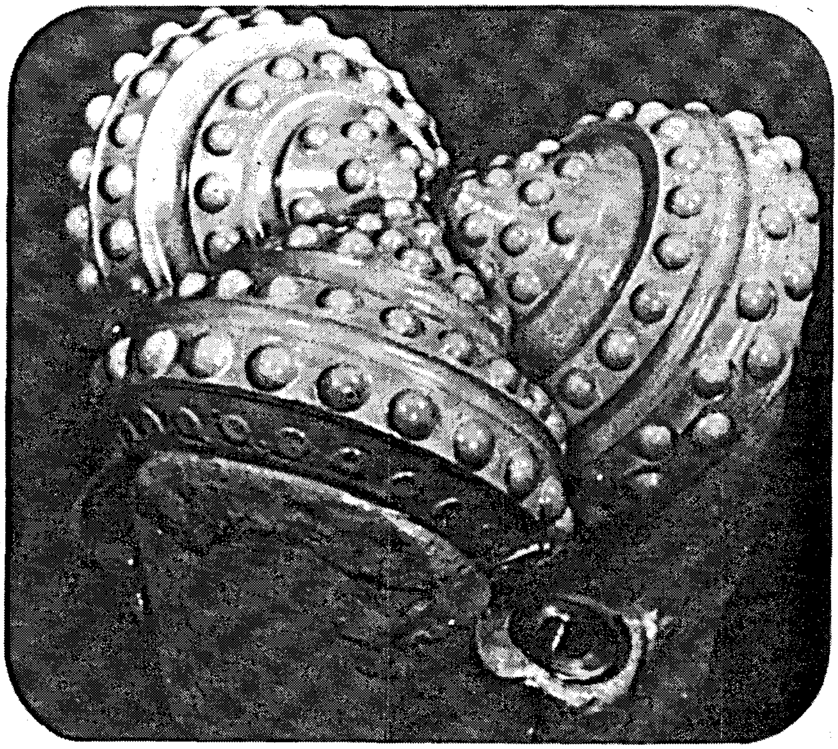

Figure 8. 9-inch M-83 hard-formation blast-hole bit, Reed Mining Tools, Inc.

thereby increasing penetration rate. Hard-formation bits cannot be used to advantage in situations such as the Geysers due to their requirement for higher bit weighting, which conventional bearings cannot support at these temperatures. The improved bearing performance provided by the CBS-600 and M-50 steels now makes it possible to build an unsealed geothermal hard formation bit for bottom-hole temperatures to 300°C.

Polycrystalline diamond, bonded to tungsten carbide inserts, has been used successfully at geothermal temperatures in drag-type bits, built by General Electric[21] and Sandia Laboratories.[22] Little, however, is know about how these inserts would perform in the cones* of a rolling-cutter bit. The

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* Garner (Sii Smith Tool Co.) was recently issued U.S. Patent No. 4,140,189 for the use of such inserts on the shank area of the lugs to improve gage cutting.

first two approaches to reducing gage-wear are therefore given the greater probability of producing near-term results.

Bearing Systems Performance - Bearing wear was reduced by a factor of two to three in all three bearing systems. Peformance is considered accepable for all components, with the exception of the ball bearings and the cone bodies. The balls wore out-of-round in a manner suggesting spalling-type failure. Selection of the ball material, and heat treat specifications need to be re-examined. The interaction between the balls and the air slots in the ball retainer plug during reaming should also be evaluated. Wear of the ball race and roller race in the cone bodies can be reduced by the use of CBS-600 steel in place of the conventional AISI 4820 alloy.

The improved high-temperature performance of the bearings can be utilized to advance several aspects of geothermal drilling:

- Higher bit weighting for faster penetration
- Longer bit life
- Higher bottom-hole temperatures
- Development of hard-formation bits
- Development of smaller roller-cone bits

It should be noted that while conventional roller-cone bits can be used for air-drilling at the Geysers, it is unlikely they will be capable of drilling anything significantly hotter than 240°C. New bearing materials would be essential for air or mist drilling where circulating bottom-hole temperatures exceed 300°C, or for mud or water drilling where circulating bottom-hole temperatures exceed 350°C.

Stabilizers and Reamers for Geysers Drilling - Improvements in the gage-wear resistance of the three-point reamers and blade stablilizers would lower

Geysers drilling costs in two ways:

- Improving stabilization of the bottom-hole assembly permits higher bit weighting where undesirable inclination or deviation of the hole are present. 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 is directly applicable to the three-point reamers. It may therefore be possible to realize further cost savings by constructing reaming cylinders from the steels and tungsten carbide used in the experimental bits.

Implications for Geysers Drilling - Reductions in drilling costs are derived from (1) improved penetration rates and (2) rig time saved by eliminating trips. A model of Geysers drilling costs, designed by the Mitre Corporation for the DOE,[23] indicated that the total well cost was eight times as sensitive to factors which influenced penetration rate as it was to costs which were not rate-related. Bit weighting at the Geysers could be increased from 133 KN (30,000 pounds) up to 178 KN (40,000 pounds), with a proportional increase in penetration rate, for some of the more ideal drilling conditions. Assuming that the higher weight could be used 20 percent of the time, a cost reduction of $70,000 per leg would result. Note that this assumes only the standard reamers and stabilizers are available.

The cost reduction associated with the 30 percent increase in usable distance drilled per bit results primarily from the rig time saved by eliminating trips. A recent cost analysis conducted by Sandia Laboratories[24] indicated a corresponding savings of $40,000 per leg in a Geysers well such as CMHC #6. This represents a 4 percent savings on the total well cost of one million dollars for the wellhead and first leg. Subsequent legs cost about $500,000 and the $40,000 represents 8 percent of this figure. The Sandia cost estimate assumes that the same break-even point analysis (i.e., amount of hole gage-loss) would be used for the new bits. It is unlikely that 5.1 mm (0.20 inch) is the correct value for the improved bits. Unfortunately, not enough is known about the relationship between the initial hole undergage condition and the gage-wear induced on the bit to determine the new break-even point at this time. The correct break-even point, and related cost reduction will hence be known only when improved bits become commercially available and a larger data base can be established.

It should also be noted that increasing bit weighting will increase the amount of usable hole obtained from the bit by an amount which is proportional to the penetration rate, assuming that gage-wear is the predominent failure mode. This is due to the fact that gage-wear is proportional to the total number of revolutions of the bit, and this is inversely proportional to penetration rate (at constant RPM). Assuming again that a 33 percent increase in penetration rate is obtained 20 percent of the time, a cost reduction of about $8,000 would accrue.

To summarize, the potential cost reduction for Geysers wells appears to be substantially greater than the $40,000 per leg figure which would result if the bits were used without optimizing drilling parameters to take better advantage of their improved bearing and cutter performance. A more reasonable estimate, as shown above, is $120,000, or 12 percent of the well cost.

CONCLUSIONS

Six 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 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 of the findings 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 bit weights (therefore, penetration rate), longer life, and the drilling of hotter formations are possible with these bits. The improved bearing materials can facilitate the construction of geothermal hard-formation type bits, and small-diameter bits (165 mm - 6-1/2 inch or less), both of which require higher strength materials.
3. While the economic benefit to the Geysers drilling application is direct and substantial (approximatley 12 percent), the experimental bits will provide markedly higher reductions in cost-per-foot and time-to-completion as more severe geothermal drilling conditions are encountered. Many future geothermal resources of the hot dry rock,

hydrothermal, and steam types, will involve severe drilling problems.

4. The favorable field test results indicate that commerical production of improved geothermal bits, utilizing some or all of these materials, or with the added improvements suggested, may now be economically viable for the bit manufacturers since no new tooling cost will be involved.

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APPENDIX A

DRILLING PERFORMANCE ANALYSIS DATA

Derivation of the Equivalent Wear Time Relationship for the Bit: The bit identification and data usage for the Drilling Performance Analysis, and for the Bearing Wear Analysis (to be discussed) are presented in Table A1.

The relationship between the effects of reaming time and drilling time was determined graphically from the well log data (Tables A2 and A3) and the gage-wear data (Table A4). The small statistical size of data available for the conventional and experimental groups dictated the use of a relatively simplistic model of the wear relationship. The results (Figure A1) were used to establish the relationship:

$$H_{BIT} = H_D + 3.2\ H_R \tag{1}$$

where:

H_{BIT} = equivalent wear time for bit (experimental or conventional)

H_D = hours of drilling

H_R = hours of reaming

Since the primary function of the bit is to drill holes, and ideally reaming should not be necessary, the "equivalent wear" was normalized in terms of drilling hours. The experimental bits, on the whole, performed better than the conventional bits due to the use of a more abrasion-resistant grade of tungsten-carbide for the inserts on gage row (see Figure A1). Drilling time for equivalent wear was improved by 5 hours, or reaming time by approximately 2 hours.

TABLE A1

BIT IDENTIFICATION AND DATA USAGE

FOR DRILLING PERFORMANCE ANALYSIS AND BEARING WEAR ANALYSIS

Trip Number[1]	Reed[2] S/N	Designation	Type	USAGE	
				Bearing Wear Analysis	Gauge Wear Analysis
16	420736	TT-1	Experimental, WC[3] Bushing	Yes	No[5]
19	420734	TT-2	Experimental, M-50 Bushing	No[4]	Yes
24	420737	TT-3	Experimental, WC[3] Bushing	Yes[6,7]	Yes
26	420735	TT-4	Experimental, M-50 Bushing	Yes[7]	Yes
45	421573	TT-5	Experimental, M-50 Bushing	Yes	Yes
43	420738	TT-6	Experimental, WC[3] Bushing	Yes[6]	Yes
17	421578	R-1	Conventional Reed Y73 JA	Yes	Yes
18	622288	None	Conventional Reed Y73 JA	No[4]	Yes
20	405110	R-2	Conventional Reed Y73 JA	No[4]	Yes
22	120850	None	Conventional Reed Y73 JA	No[4]	Yes
25	119447	R-3	Conventional Reed Y73 JA	Yes[7]	Yes
27	118861	R-4	Conventional Reed Y73 JA	Yes[7]	Yes
41	405111	R-5	Conventional Reed Y73 JA	Yes	No[8]
44	434944	R-6	Conventional Reed Y73 JA	Yes	Yes

[1]Each drilling trip in the CMHC #6 well was assigned a consecutive number.
[2]Reed Rock Bit Company, Houston, Texas; formerly Reed Tool Company.
[3]General Electric Carboloy #248 pilot bushings in cones.
[4]Bit was subjected to excessive reaming, causing atypical bearing wear.
[5]Bit drilled a softer formation than other bits.
[6]One bushing broke or disintegrated, but all other available measurements were used.
[7]Only two of three lugs measured; others used for metallurgical analysis.
[8]Gage wear data for reamers and stabilizers was not available for this bit.

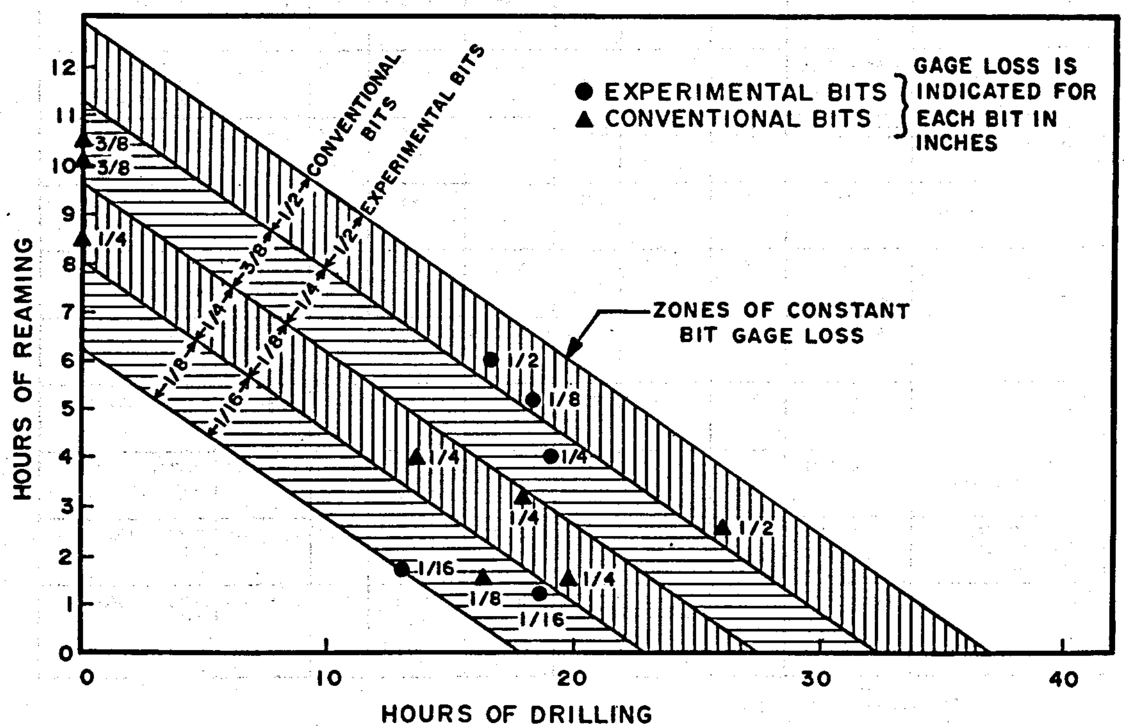

Figure A1. Bit gage loss as a function of reaming time and drilling time.

TABLE A2

WELL LOG DATA FOR CMHC #6, LEG #1

TRIP NO.	BIT	USE	FOOTAGE REAMED	REAMING, HOURS	FOOTAGE DRILLED	DRILLING HOURS*	WEIGHT ON BIT KIP	RPM	BIT COND. T-B-G**	NOTES
16	EXPERIMENTAL W-C BUSHING #420736	REAM & DRILL	221	3 1/4	688	27 1/4	25-32	70-75	4, 2, 1/16	EXCELLENT CONDITION PREVIOUS BIT WAS 1/16 UNDERGAGE
17	REED Y73JA (CONVENTIONAL) #421578	REAM & DRILL	222	2 1/2	538	26	25	70-75	8, 8, 1/2	RUN TOO LONG, CAUSED SEVERE LOSS OF GAGE IN HOLE
18	REED Y73JA (CONVENTIONAL) #622288	REAM ONLY	487	10	NONE	NONE	0-5	-	3, 3, 3/8	EXCESSIVE GAGE WEAR
19	EXPERIMENTAL M-50 BUSHING #420734	REAM & DRILL	361	6	250	16 3/4	20-25	70-72	8, 8, 1/2	EXCESSIVE REAMING, WENT INTO 3/8 UNDERGAGE HOLE
20	REED Y73JA (CONVENTIONAL) #405110	REAM ONLY	364	8 1/2	NONE	NONE	0-5	50-55	6, 8, 1/4	EXCESSIVE GAGE WEAR
21	(TYPE & MODEL NUMBER NOT AVAIL-ABLE)	REAM ONLY	151	5 3/4	NONE	NONE	0-5	50-55	6, 7, 1/4	EXCESSIVE GAGE WEAR
22	REED Y73JA (CONVENTIONAL BIT) #120850	REAM ONLY	358	10 1/2	NONE	NONE	0-5	50-55	4, 6, 3/8	EXCESSIVE GAGE WEAR
23	(TYPE & MODEL NUMBER NOT AVAIL-ABLE)	REAM & DRILL	251	4	DRILLING DATA NOT AVAILABLE				5, 6, 1/8	
24	EXPERIMENTAL W-C BUSHING #420737	REAM & DRILL	287	3 1/2	203	18 1/2	20-25	50-55	4, 4, 1/16	MINIMAL LOSS OF GAGE
25	REED Y73JA (CONVENTIONAL) #119447	REAM & DRILL	160	1 1/2	190	19 3/4	20-23	48-50	5, 6, 1/4	EXCESSIVE GAGE WEAR
26	EXPERIMENTAL M-50 BUSHING #420735	REAM & DRILL	412	5 1/4	288	18 1/4	20-23	40-60	4, 5, 1/8	MODERATE LOSS OF GAGE
27	REED Y73JA (CONVENTIONAL) #118861	REAM & DRILL	292	3 1/4	352	18	20-23	60	5, 6, 1/4	EXCESSIVE GAGE WEAR

*Does not include reaming time.

**Bits are graded by the driller when pulled from the hole:
"T" (tooth) designated cutting structure wear
"B" designates bearing wear
"G" gage loss in inches
"T" and "B" are graded on a scale of 0 (new) to 8 (totally worn out).
The gage losses shown are 2/3 of actual measurement, which is standard rating procedure.

TABLE A3

WELL LOG DATA FOR CMHC #6, LEG #2

TRIP NO.	BIT	USE	FOOTAGE REAMED	REAMING, HOURS	FOOTAGE DRILLED	DRILLING HOURS*	WEIGHT ON BIT KIP	RPM	BIT COND. T-B-G**
38	(TYPE & MODEL NUMBER NOT AVAILABLE)	REAM & DRILL	407	6 3/4	176	9 1/2	30	60	8, 8, 7/8
39	(TYPE & MODEL NUMBER NOT AVAILABLE)	REAM ONLY	526	7 3/4	NONE	NONE	5-10	60-65	7, 7, 1/2
40	(TYPE & MODEL NUMBER NOT AVAILABLE)	REAM & DRILL	60	1 1/2	105	9 1/2	30	55-60	4, 5, 1/4
41	REED Y73JA (CONVENTIONAL) #405111	REAM & DRILL	220	3 3/4	156	8 1/4	30	60-65	5, 6, 3/16
42	(TYPE & MODEL NUMBER NOT AVAILABLE)	REAM & DRILL	338	4 1/2	95	8 1/4	30	55-60	3, 4, 1/8
43	EXPERIMENTAL W-C BUSHING #420738	REAM & DRILL	330	4	316	19	35K	55-60	4, 5, 1/4
44	REED Y73JA (CONVENTIONAL) #434944	REAM & DRILL	282	4	191	13 1/2	35K	55-60	4, 6, 1/4
45	EXPERIMENTAL M-50 BUSHING #421573	REAM & DRILL	201	1 3/4	188	13	35K	55-60	3, 5, 1/8
46	REED Y73JA (CONVENTIONAL) #434946	REAM & DRILL	160	N/A	258	16 1/4	35K	55-60	6, 5, 1/16

*Does not include reaming time.

**Bits are graded by the driller when pulled from the hole:
"T" (tooth) designated cutting structure wear
"B" designates bearing wear
"G" gage loss in inches
"T" and "B" are graded on a scale of 0 (new) to 8 (totally worn out).
The gage losses shown are 2/3 of actual measurement, which is the standard rating procedure.

TABLE A4

GAGE-WEAR OF BOTTOM-HOLE ASSEMBLIES

Trip No.	Bit Type	Bit Rating[1] T	B	GAGE WEAR, MILLIMETERS (INCHES)[2] Bit	Reamer	Lower Stabilizer	Upper Stabilizer
16	WC	4	2	1.6 (1/16)	Not Used	4.8 (3/16)	6.4 (1/4)
17	Y73	8	8	12.7 (1/2)	15.9 (5/8)	9.5 (3/8)	6.4 (1/4)
18	Y73	3	3	9.5 (3/8)	N.A.	N.A.	N.A.
19	M-50	8	8	12.7 (1/2)	12.7 (1/2)	9/5 (3/8)	6.4 (1/4)
20	Y73	6	8	6.4 (1/4)	12.7 (1/2)	3.2 (1/8)	3.2 (1/8)
22	Y73	4	6	9.5 (3/8)	6.4 (1/4)	3.2 (1/8)	3.2 (1/8)
24	WC	4	4	1.6 (1/16)	12.7 (1/2)	4.8 (3/16)	3.2 (1/8)
25	Y73	5	6	6.4 (1/4)	4.8 (3/16)	3.2 (1/8)	6.4 (1/4)
26	M-50	4	5	3.2 (1/8)	15.9 (5/8)	4.8 (3/16)	6.4 (1/4)
27	Y73	5	6	6.4 (1/4)	9.5 (3/8)	6.4 (1/4)	6.4 (1/4)
41	Y73	5	6	4.8 (3/16)	N.A.	N.A.	N.A.
43	WC	4	5	6.4 (1/4)	N.A.	N.A.	N.A.
44	Y73	4	6	6.4 (1/4)	12.7 (1/2)	3.2 (1/8)	3.2 (1/8)
45	M-50	3	5	3.2 (1/8)	4.8 (3/16)	3.2 (1/8)	3.2 (1/8)

[1]Bits are graded by the driller when pulled from the hole:
"T" (tooth) designated cutting structure wear.
"B" designates bearing wear.
"T" and "B" are graded on a scale of 0 (new) to 8 (totally worn out).

[2]The gage losses shown are 2/3 of actual measurement, which is the standard rating procedure. Readings are taken in fractions of an inch.

Hole Drilled to Gage, and In-Gage Equivalent Wear Time: In all drilling situations the bit initially drills a slightly over-gage hole due to non-concentric rotation, and due to bit design*. In wells where gage loss is moderate to severe, the bit will wear to an under-gage condition prior to the end of its useful life. The depth at which this occurs can be determined by locating the point where the next bit began reaming. Table A5 compares reaming time, total drilling time, 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.

The data presented in Table A5 facilitate evaluation of the experimental and conventional bits in three ways:

- Distance drilled in-gage
- Hours of in-gage drilling
- In-gage equivalent wear time

The experimental bits drilled an average of 60.4 m (198 feet) in-gage, as compared to 33.2 m (109 feet) for the conventional bits; this represents an improvement of 82 percent.

Drilling time is a better indicator of overall bit performance than is distance, since it tends to normalize differences in formation drillability. The experimental bits drilled an average of 11.5 hours, in-gage as opposed to 6.8 hours in-gage for the conventional bits, yielding a 70 percent improvement.

The average hours of in-gage "equivalent wear time" were also calculated for the two groups, using Equation (1). The 20.7 hours for the experimental

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* The Y73 JA bits and the experimental bits were manufactured 1.3 mm (0.05 inches) over gage-standard practice for this model bit.

TABLE A5

IN-GAGE REAMING AND DRILLING

Trip No.	Bit Type	Bit Rating[1] T	B	GAGE WEAR, MILLIMETERS (INCHES)[2] Bit	Reamer	Lower Stabilizer	Upper Stabilizer
16	WC	4	2	1.6 (1/16)	Not Used	4.8 (3/16)	6.4 (1/4)
17	Y73	8	8	12.7 (1/2)	15.9 (5/8)	9.5 (3/8)	6.4 (1/4)
18	Y73	3	3	9.5 (3/8)	N.A.	N.A.	N.A.
19	M-50	8	8	12.7 (1/2)	12.7 (1/2)	9/5 (3/8)	6.4 (1/4)
20	Y73	6	8	6.4 (1/4)	12.7 (1/2)	3.2 (1/8)	3.2 (1/8)
22	Y73	4	6	9.5 (3/8)	6.4 (1/4)	3.2 (1/8)	3.2 (1/8)
24	WC	4	4	1.6 (1/16)	12.7 (1/2)	4.8 (3/16)	3.2 (1/8)
25	Y73	5	6	6.4 (1/4)	4.8 (3/16)	3.2 (1/8)	6.4 (1/4)
26	M-50	4	5	3.2 (1/8)	15.9 (5/8)	4.8 (3/16)	6.4 (1/4)
27	Y73	5	6	6.4 (1/4)	9.5 (3/8)	6.4 (1/4)	6.4 (1/4)
41	Y73	5	6	4.8 (3/16)	N.A.	N.A.	N.A.
43	WC	4	5	6.4 (1/4)	N.A.	N.A.	N.A.
44	Y73	4	6	6.4 (1/4)	12.7 (1/2)	3.2 (1/8)	3.2 (1/8)
45	M-50	3	5	3.2 (1/8)	4.8 (3/16)	3.2 (1/8)	3.2 (1/8)

[1]Bits are graded by the driller when pulled from the hole:
"T" (tooth) designated cutting structure wear.
"B" designates bearing wear.
"T" and "B" are graded on a scale of 0 (new) to 8 (totally worn out).

[2]The gage losses shown are 2/3 of actual measurement, which is the standard rating procedure. Readings are taken in fractions of an inch.

bits represents a 30 percent increase over the 15.9 hours for the comparative group.

<u>Derivation of the Equivalent Wear Time Relationship for the Bottom-Hole Assembly (BHA)</u>: The analytical approach is the same as was used for determining the equivalent wear time relationship for the bit. The relationship between reaming time and drilling time was determined graphically from the gage-wear data (Table A4) and the well log data (Tables A2 and A3). The lowest of the four ring-gage measurements made on each BHA was taken to represent the gage loss for the BHA, and also the hole which it drilled. Each BHA was then plotted as a point, with its gage loss, as a function of reaming hours and drilling hours (Figure A2). The slope of the "zones of equivalent gage loss" was then used to establish the relationship:

$$H_{BHA} = H_D + 2.5\ H_R \tag{2}$$

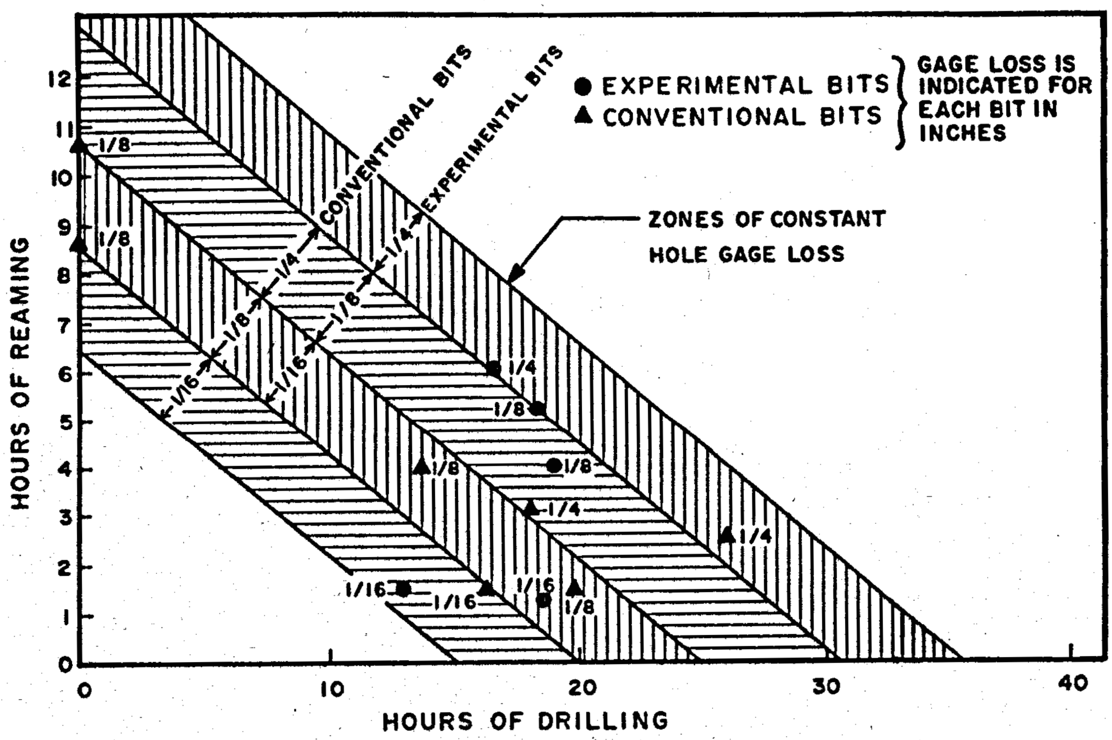

Figure A2. Bottom-hole assembly gage loss as a function of reaming time and drilling time.

where:

H_{BHA} = hours of equivalent wear time for BHA (with experimental or conventional bit)

H_D = hours of drilling

H_R = hours of reaming

The coupling of the bit performance with BHA wear is clearly seen in Figure A2. The experimental bit improved the drilling time possible by 5 hours, or reaming time by 2 hours.

Disassembly: All bits were disassembled using a water-cooled horizontal band saw to cut the lugs. Ball retainer plugs and the ball bearings were then removed, thus permitting removal of the cone and rollers.

Measurement Details: The bearing wear measurements are presented in Tables A6 and A7. Each lug and cone set was measured for wear at sixteen locations, as illustrated in Figure A3. Six balls and six rollers from each set were measured for minimum and maximum diameter (12 readings per set). Minimum, maximum and average wear values are provided for each set of 12 measurements*.

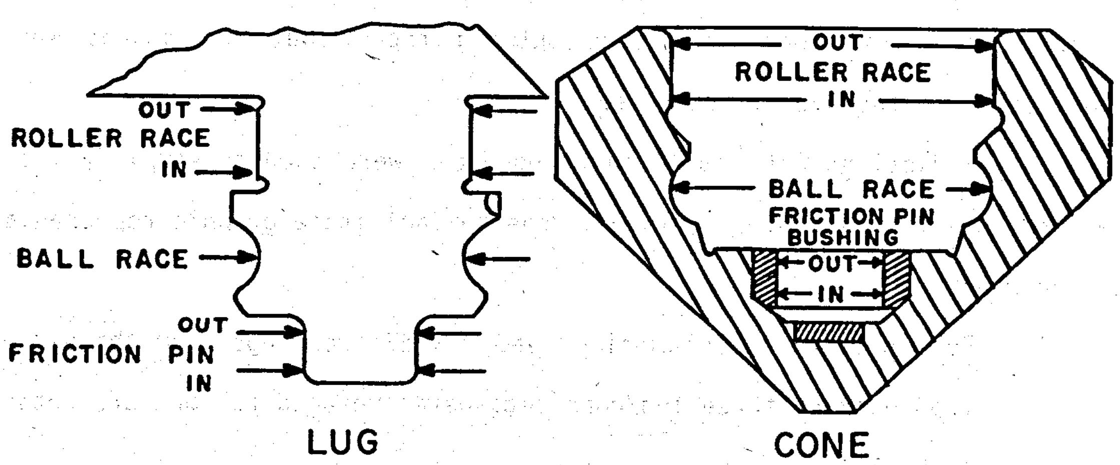

Figure A3. Wear Measurement Locations

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* Hence average ball or roller wear is not derived by averaging the "MINIMUM" and "MAXIMUM" values presented in the Tables.

Lug wear was characterized in both the horizontal and vertical directions. The wear values for the vertical measurements are generally much greater than the horizontal measurements since wear occurs predominantly on the underside of the lug. The orientation of each lug measurement is denoted in the table. Measurements for the ball race were taken at plus and minus 30° from vertical to avoid the ball entry hole.

Lug and cone wear was generally non-uniform in the roller bearing races and friction pin area. Wear measurements were made at the inward and outward extremes of the roller race and friction pin of the lugs, and the roller race and bushing of the cones, as illustrated in Figure A3, to characterize the taper wear. The taper values provided in Table A3 are the difference between the associated "IN" and "OUT" wear measurements. Where the taper indicates an increase in the effective journal angle (cone tilt) the taper is designated "OUT".* The opposite condition is designated "IN". Both the conventional and experimental bits experienced some outward taper, but the amount was not significant to the overall results.

Data Reduction: The following procedures were used to simplify the wear measurements for each bit. This was done to facilitate graphic representation of the wear.

1. Ball bearings - The minimum and maximum readings from the six balls from each of three lug/cone sets were averaged (36 measurements from 18 balls).

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* This condition is referred to as "running out", and results in an increase in wellbore diameter; outward taper is therefore less undesirable than is inward taper. All taper is undesirable since it causes roller skew and cone lock-up, and generally shortens the life of the carburized roller races on the lug and the cone.

2. Roller bearings - Same as for ball bearings.

3. Lug wear - All horizontal measurements and taper calculations were discarded.

   A. Ball race - the +30° and -30° measurements from each lug (total of 6 measurements) were averaged.

   B. Roller race - The vertical "IN" and "OUT" measurements from the three lugs (total of 6) were averaged.

   C. Friction pin - Same as for roller race.

4. Cone Wear - Nearly all bearing surfaces on the cones were round to within 0.001 inches. Where necessary, an average value was calculated.

   A. Ball race - The three cones were averaged.

   B. Roller race - The "IN" and "OUT" measurements for the three cones (total of six measurements) were averaged.

   C. Friction Pin (bushing) - Same as for roller race.

These procedures reduced the 120 measurements taken on each bit to eight composite wear values. Averages were then calculated for each of the three types of bits (conventional, M-50 bushing, and WC bushing), using only the bits specified in Table A1. These were used to prepare the horizontal bar chart shown in Figure 6.

TABLE A6

BEARING WEAR DATA FOR CONVENTIONAL BITS: REED ROCK BIT COMPANY
Y73-JA 222 mm (8-3/4 inch) Unsealed Air Type

All Data are in Inches

BIT	R-1			R-2			R-3			R-4			R-5			R-6		
LUG NUMBER	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
FEET DRILLED		538			0			190			352			156			191	
HOURS DRILLED		26			0			19.75			18			8.25			13.5	
FEET REAMED		222			364			160			292			220			282	
HOURS REAMED		2.5			8.5			1.5			3.25			3.75			4	
BALL BEARING WEAR:																		
AVERAGE	.030	.031	.027	.000			.005	.005	.006	.000	.000	.005	.003	.006	.010	.003	.002	.004
HIGH	.062	.051	.073	.000			.008	.009	.008	.000	.000	.006	.004	.012	.017	.005	.004	.011
LOW	.018	.024	.024	.000			.003	.003	.005	.000	.000	.005	.002	.005	.006	.000	.000	.000
ROLLER BEARING WEAR	.004 .007	.005 .011	.005 .009	.000			.002	.001	.002	.001	.002	.002	.004	.004	.003	.000	.000	.000
LUG WEAR:																		
BALL RACE ↘	.091	.100	.101	.009			.020		.026		.023	.032	.037	.030	.025	.024	.024	.020
BALL RACE ↗	.081	.104	.089	.006			.020		.025		.025	.033	.042	.028	.024	.025	.027	.022
BALL RACE ↔	.013	.014	.014	.001			.008		.010		.007	.008	.008	.013	.007	.008	.008	.005
ROLLER RACE IN ↕	.093	.119	.119	.003			.016		.019		.022	.032	.027	.023	.020	.014	.017	.011
ROLLER RACE OUT ↕	.060	.094	.089	.006			.012		.014		.020	.021	.015	.015	.013	.012	.012	.010
R. RACE TAPER ↕	.033	.025	.030	.003			.004		.005		.002	.011	.012	.008	.017	.002	.005	.001
ROLLER RACE IN ↔	.006	.006	.008	.001			.004		.003		.004	.005	.007	.005	.005	.004	.005	.001
ROLLER RACE OUT ↔	.005	.010	.009	.001			.004		.004		.004	.004	.008	.005	.004	.005	.007	.002
R. RACE TAPER ↔	.001	.004	.001	.000			.000		.001		.000	.001	.001	.000	.001	.001	.002	.001
FRICTION PIN IN ↕	.085	.087	.085	.010			.032		.031		.018	.031	.027	.019	.016	.020	.023	.015
FRICTION PIN OUT ↕	.089	.092	.089	.009			.027		.025		.013	.030	.029	.028	.036	.021	.016	.015
F.P. TAPER ↕	.004	.005	.004	.001			.005		.006		.005	.001	.002	.008	.020	.001	.007	.000
FRICTION PIN IN ↔	.006	.002	.006	.000			.009		.007		.004	.006	.003	.004	.004	.001	.006	.002
FRICTION PIN OUT ↔	.006	.001	.003	.000			.001		.002		.004	.006	.004	.008	.006	.004	.004	.005
F.P. TAPER ↔	.000	.001	.003	.000			.008		.005		.000	.000	.001	.004	.002	.003	.002	.003
CONE WEAR:																		
BALL RACE	.026	.025	.025	.016			.015	.014	.015	.017	.016	.016	.018	.016	.017	.016	.014	.014
ROLLER RACE IN	.021	.029	.027	.002			.007	.008	.010	.013	.012	.016	.011	.011	.009	.006	.006	.005
ROLLER RACE OUT	.044	.042	.049	.001			.007	.010	.010	.016	.023	.034	.008	.011	.012	.003	.006	.005
ROLLER RACE TAPER	.023	.013	.022	.001			.000	.002	.000	.003	.011	.018	.003	.000	.003	.003	.000	.000
FRICTION PIN IN	.119	.149	.129	.037			.015	.024	.028	.032	.022	.033	.070	.048	.041	.047	.032	.034
FRICTION PIN OUT	.111	.137	.124	.020			.011	.019	.016	.037	.023	.039	.074	.040	.022	.040	.033	.039
FRICTION PIN TAPER	.008	.012	.005	.017			.004	.005	.012	.005	.001	.006	.004	.008	.019	.007	.001	.005

TABLE A7

BEARING WEAR DATA FOR EXPERIMENTAL BITS: 222 mm (8-3/4 inch) Unsealed Air Type

All Data are in Inches

	Carbide			M-50			Carbide			M-50			M-50			Carbide		
BIT	TT-1			TT-2			TT-3			TT-4			TT-5			TT-6		
LUG NUMBER	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
FEET DRILLED		688			250			290			288			316			188	
HOURS DRILLED		27.25			16.75			18.5			18.25			19			13	
FEET REAMED		221			361			287			412			330			201	
HOURS REAMED		3.25			6			3.5			5.25			4			1.75	
BALL BEARING WEAR:																		
AVERAGE	.009	.019	.013	.041	.067	.024	.010	.015	.013	.004	.004	.005	.012	.018	.012	.008	.022	.014
HIGH	.014	.028	.028	.041	.067	.025	.016	.024	.031	.005	.006	.012	.023	.026	.017	.040	.023	.051
LOW	.005	.008	.007	.040	.066	.024	.004	.011	.009	.003	.001	.003	.009	.011	.007	.007	.022	.013
ROLLER BEARING WEAR	.002	.002	.002	.001	.001	.001	.000	.000	.000	.001	.000	.000	.001	.001	.001	.000	.000	.000
LUG WEAR:																		
BALL RACE ↘	.013	.013	.012	.036	.060	.036	.010		.009	.017		.017	.012	.011	.015	.020	.030	.022
BALL RACE ↗	.014	.015	.016	.033	.042	.031	.013		.009	.017		.016	.011	.013	.015	.022	.032	.023
BALL RACE ↔	.007	.006	.004	.007	.008	.007	.005		.004	.005		.007	.006	.005	.005	.009	.008	.006
ROLLER RACE IN ↕	.010	.014	.015	.035	.067	.026	.009		.011	.016		.016	.013	.013	.010	.013	.026	.016
ROLLER RACE OUT ↕	.004	.012	.011	.004	.023	.010	.007		.008	.011		.014	.011	.009	.008	.003	.008	.007
R. RACE TAPER ↕	.006	.002	.004	.029	.043	.016	.002		.003	.005		.002	.002	.004	.002	.010	.018	.009
ROLLER RACE IN ↔	.000	.001	.000	.001	.003	.000	.000		.000	.001		.002	.001	.003	.002	.000	.000	.002
ROLLER RACE OUT ↔	.000	.000	.000	.000	.002	.000	.000		.000	.001		.002	.000	.001	.000	.000	.000	.003
R. RACE TAPER ↔	.000	.001	.000	.001	.001	.000	.000		.000	.000		.000	.001	.002	.002	.000	.000	.001
FRICTION PIN IN ↕	.026	.021	.024	.048	.069	.035	.021		.014	.020		.018	.010	.013	.007	.035	.275	.045
FRICTION PIN OUT ↕	.027	.025	.026	.050	.067	.043	.019		.019	.018		.019	.008	.008	.011	.041	.129	.050
F.P. TAPER ↕	.001	.004	.002	.002	.002	.008	.002		.005	.002		.001	.002	.005	.004	.006	.144	.005
FRICTION PIN IN ↔	.003	.008	.005	.004	.002	.005	.007		.004	.004		.007	.004	.004	.003	.010	.129	.018
FRICTION PIN OUT ↔	.007	.011	.005	.004	.003	.005	.006		.007	.004		.005	.003	.001	.002	.012	.082	.023
F.P. TAPER ↔	.004	.003	.000	.000	.001	.000	.001		.003	.000		.002	.001	.003	.001	.002	.047	.005
CONE WEAR:																		
BALL RACE	.005	.004	.008	.020	.018	.012		.005	.002	.008		.004	.004	.003	.004	.009	.010	.005
ROLLER RACE IN	.008	.012	.016	.004	.024	.010		.011	.012	.014		.012	.011	.013	.014	.016	.025	.019
ROLLER RACE OUT	.007	.012	.016	.021	.113	.017		.008	.009	.017		.017	.010	.009	.016	.018	.025	.018
ROLLER RACE TAPER	.001	.000	.000	.017	.089	.007		.003	.003	.003		.005	.001	.004	.002	.002	.000	.001
FRICTION PIN IN	.010	.008	.011	.202	.231	.156			.003	.024		.012	.015	.026	.016	.010		.008
FRICTION PIN OUT	.008	.005	.010	.193	.219	.141			.002	.020		.014	.021	.034	.015	.009		.005
FRICTION PIN TAPER	.002	.003	.001	.009	.012	.015			.001	.004		.002	.006	.008	.001	.001		.003

R1/B

APPENDIX B

ANNUAL REPORT

SUPPORT RESEARCH FOR DEVELOPMENT OF IMPROVED GEOTHERMAL DRILL BITS

by

R.R. Hendrickson
R.W. Winzenried
A.H. Jones
S.J. Green

Submitted to

Department of Energy
Division of Geothermal Energy
Attention: Dr. Samuel G. Varnado
Sandia Laboratories

Submitted by

Terra Tek, Inc.
University Research Park
420 Wakara Way
Salt Lake City, Utah 84108

TR78-41
July, 1978

FOREWORD

This represents the annual progress report for DOE Contract EG-76-C-7-1546, aimed at research to support development of improved geothermal rolling-cutter drill bits.

MATERIALS SELECTIONS FOR MK-III EXPERIMENTAL DRILL BITS

A planning meeting was held at Reed Tool Company of August 9, 1977, to finalize the materials selections and heat-treat specifications for the MK-III experimental bits*; the minutes of these meetings are given in Appendix A. It was agreed that Terra Tek would provide the balls, rollers, nose bushings, and materials for the lugs, and Reed Tool Company would provide the cones and carbide drilling inserts, as well as all of the manufacturing, on a no-cost basis. The program included six bits for field testing, and two for evaluation in the Drilling Research Laboratory. The materials selected for the MK-III bits are illustrated in Figure 11.

The "manufacturability" of candidate steels was a primary consideration, since geothermal bit components must be manufactured on the same production equipment as conventional bits; the present geothermal bit market is not large enough to justify large expenditures for tooling. Any candidate steel must therefore lend itself to forging, heat-treating, carburizing, and machining in a manner similar to AISI 8620 (lugs) and AISI 4820 (cones).

In addition, the question of hydrogen embrittlement was considered, due to the presence of hydrogen-sulfide gas in many geothermal wells. A thorough investigation of the subject was made and is presented in Appendix B. The report concludes that there is no known defense against hydrogen embrittlement, other than keeping the strength of the steel as low as possible. Since brittle failure was not a common failure-mode for

*Additional details were finalized during a program review meeting at Terra Tek on September 7, 1977.

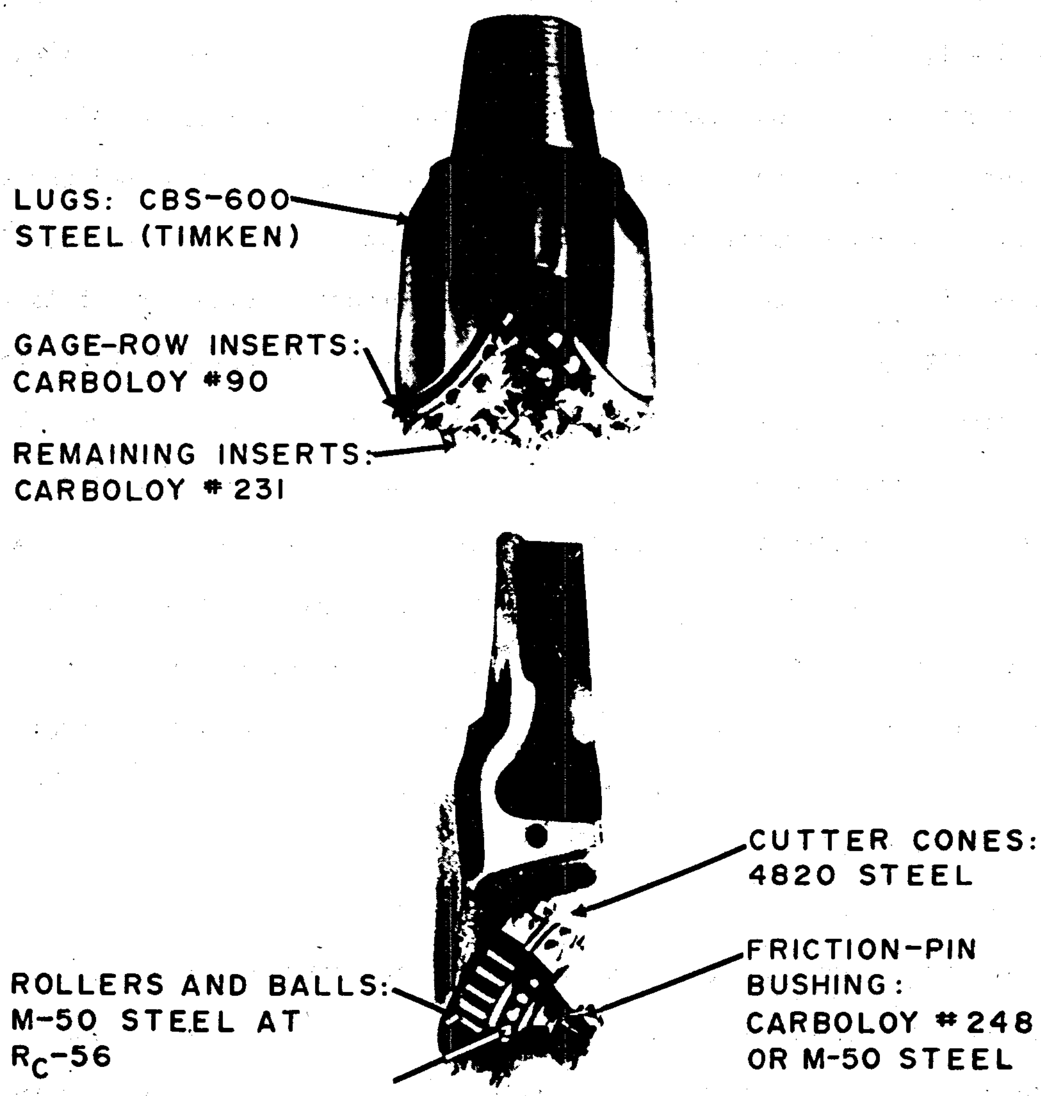

Figure 11. Materials selected for third generation of experimental unsealed bits.

bits used in geothermal wells, it was concluded that strength levels in experimental steels should be held to approximately the same level as conventional bits (at lower temperatures) to minimize the risk of brittle failure.

The following is a review of the materials selections for each component of the MK-III bits, including a discussion of specific problems, and a presentation of materials property test data.

LUGS - The materials requirements for the lugs are the most demanding of all the bit components: a high level of toughness is required to avoid breakage, in addition to the need for retention of hardness in the area of the bearing races.* Lugs lacking in fracture toughness tend to break off where the roller race joins the vertical portion of the lug; Figure 3 illustrates a typical failure. Optimization of bit geometry for maximum drilling efficiency results in a relatively small lug cross-section, with resultant high stress concentrations; the high dynamic stresses which occur in drilling further aggravate this situation. The material, carburizing, and heat-treating for the lugs of conventional bits (AISI 8620) have been highly refined to meet the requirements of hardness, strength and fracture toughness.

Steels were sought for the MK-III bit lugs which maintained levels of toughness, strength and hardness at 300°C which were roughly equivalent to those of AISI 8620 at room temperature. Timken CBS-1000M, Teledyne-Vasco X2 CVM "modified", and Timken CBS-600 appeared promising, based on manufacturer's data (composition of all steels used in the program are given

*Note that nearly all wear on the lug races is concentrated on the underside, whereas the wear of the cone races is distributed over the entire circumference, an area which is roughly six times as large as the load-bearing area on the lug.

in Table I). The first two candidates were set aside due to requirements for temperatures in carburizing and heat treating which were above the capabilities of manufacturers' facilities. Data provided by Timken, however, indicated that CBS-600 possessed the required materials properties in addition to lending itself to all aspects of manufacturing: little or no alterations to forging and machining equipment, and minor changes in carburizing and heat-treating procedures. Figure 12 shows retention of bearing surface hardness (1 percent carbon) as a function of temperature for CBS-600 and 8620. The CBS-600 retains a hardness of about R_C 54.5 at 300°C, versus 46 for 8620. Additional data supplied by Timken indicated negligible decarburation for 100-hour exposure to air at 300°C.*

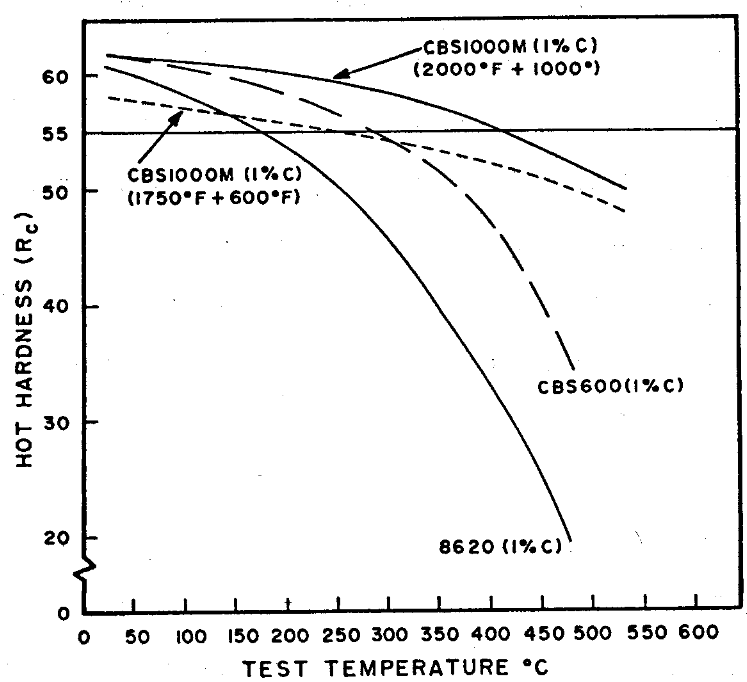

Figure 12. Hardness versus temperature for bit lug materials. (Timken Corporation)

*Decarburizing may be increased by the high air velocity in the bearing areas due to the purge flow. Microhardness measurements will be performed on tested bits to determine the extent of decarburization.

The method most widely used for measuring the toughness of steels is the Charpy V-notch test, in which a pendulum is used to break off a notched sample, and the foot-pounds of energy given up by the pendulum is taken to be the "impact energy" of the material. The Charpy test is simple and fast, but results are dependent on sample size, and are therefore not a measure of a material property. Fracture-toughness tests, when performed in accordance with ASTM specification E399-74, provide a materials property measurement (K_{Ic}) which is independent of sample size; the K_{Ic} value is derived from the energy required to advance a crack through a measured area of the material. There is currently no algorithm available to convert Charpy energies to fracture toughness, and the latter is therefore the preferable measure of a material's resistance to brittle failure.

Charpy V-notch data are provided by Timken for 4820, CBS-600 and CBS-1000M (Figure 13); 4820 is actually used for cones, and data on 8620 would be preferable, but toughness levels and transition temperatures for the two are similar.

Fracture-toughness tests were performed on four samples of CBS-600, having a uniform hardness of R_C 35, at temperatures from 150°C to 300°C (Figure 14). Unfortunately, comparative laboratory-fracture toughness

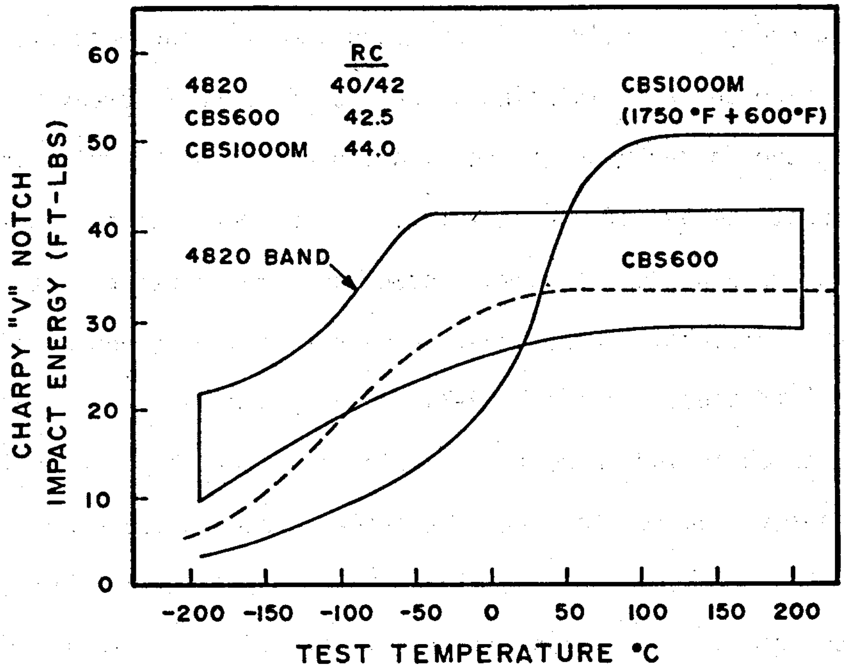

Figure 13. Charpy impact energies for uncarburized cores of CBS-600, 4820, and CBS-1000M as a function of temperature (Timken data).

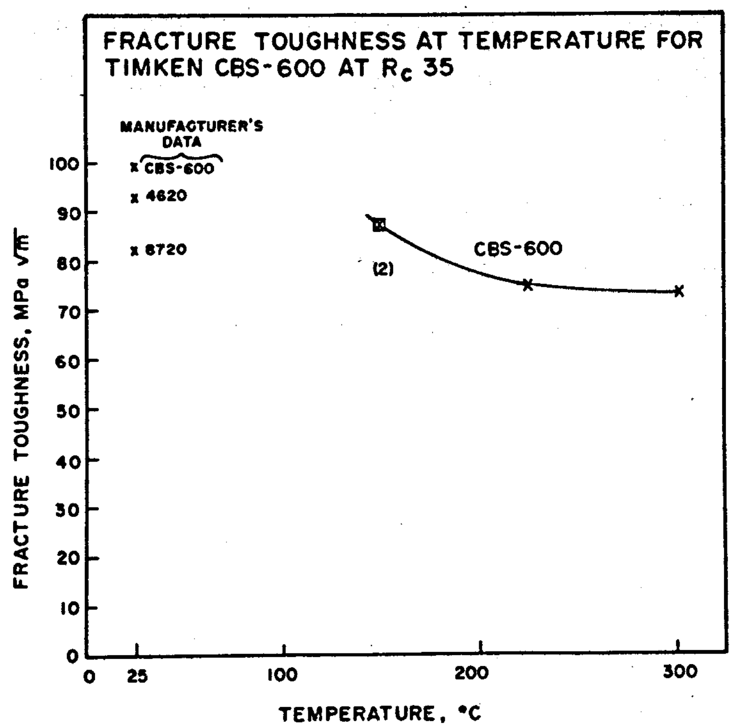

Figure 14. Fracture toughness of Timken CBS-600 (R_C 35) versus temperature as determined by laboratory tests (room temperature points for CBS-600, 4620, and 8720 are Timken data).

tests on 8620 and 4820, run two years previous to the CBS-600, were found to be invalid due to the use of too small a sample size. However, the room-temperature K_{Ic} measurements provided by Timken (see Figure 14) are encouraging since they indicate superior toughness for the CBS-600 at room temperature, and toughness for the CBS-600 at 300°C which is roughly equivalent to 8720 at 25°C.

Figure 15 shows the results of end-quench hardenability data (Jominy curves) for CBS-600 and 4820; note that the CBS-600 attains higher hardness (strength) almost uniformly through the sample. Table IV compares core strengths for 4820, CBS-600 and CBS-1000M at various temperatures; adequate core strength is necessary to support bearing areas and to prevent bending.

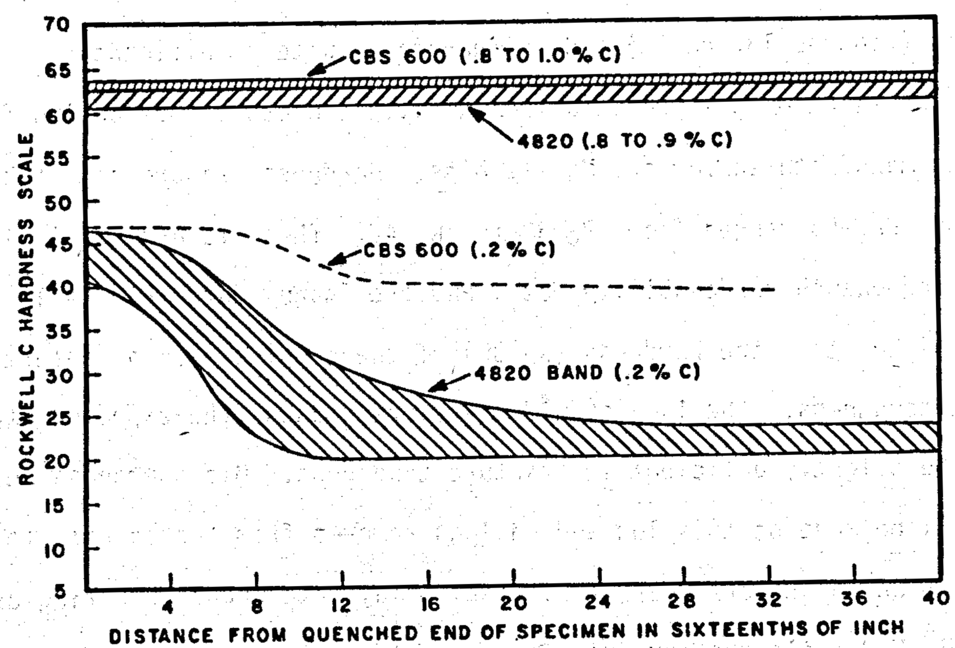

Figure 15. End-quench hardenability for 4820 and CBS-600 (Timken data).

TABLE IV

COMPARISON OF CORE MECHANICAL PROPERTIES FOR CBS-600, 4820 AND CBS-1000M (ALL DATA SUPPLIED BY TIMKEN)

Material	Size	Test Temp C°(°F)	.2% Yield KSI	Ultimate Tensile KSI	% Elongation	% Reduction of Area
4820	2" Rd.	20(70)	93	136	20	56
CBS-600	2" Sq.	20(70)	118	170	17	55
CBS-600	2" Sq.	316(600)	152	215	18	52
CBS-1000M	4" Rd.	20(70)	174	212	16	64
CBS-1000M	4" Rd.	427(800)	146	184	12	52

The data indicate more than adequate strength for the CBS-600 at 20°C and 300°C. Note that the higher strength was attained without sacrificing toughness (Figures 13 and 14) and is therefore quite significant.

A cross-section was prepared from a fully processed CBS-600 lug from the batch manufactured for the MK-III bits. Hardness measurements taken at various depths ranged from R_C 38 to R_C 42. These values are in line with the end-quench hardenability data, and the Charpy data (Figure 15 and 13), but are higher than the hardness (R_C 35) of the samples used to determine fracture toughness. The lugs should therefore possess the expected strength, but may be slightly deficient in fracture toughness. Microhardness measurements will be made on this lug and on lugs removed from tested bits to characterize any annealing or decarburizing which may have occurred during drilling.

Table V details the carburizing and heat treating for the MK-III lugs. The hardening temperature was increased to that used for conventional 8620 lugs so that this step could be carried out on a normal production run.

TABLE V

HEAT TREATING PROCEDURES FOR CBS-600 LUGS

	Procedure Recommended by Timken	Actual Procedure Used by Reed Tool
Carburizing	927/954°C (1700/1750°F)	927°C (1700°F) 16 hours
Quench	Oil at Room Temperature	Oil at Room Temperature
Condition	593/704°C (1100/1300°F)	650°C (1200°F) 1 hour
Hardening	843°C (1550°F) can also be single-quenched from carburizing or double-quenched from 927°C (1700°F) hardening temperature	899°C (1650°F)
Quench	Oil at Room Temperature	Oil at Room Temperature
Temper	Double-temper at 316°C (600°F)	Single Temper at 316°C (600°F)

CONES - The steel selected for the cones was AISI #4820, the same steel used on conventional bits. The cone wear measured on laboratory-tested conventional bits ("A", "B"[13], "E"[13], and "F"[13]) was considered less significant than the wear on the lug, balls and rollers (see Appendix A). In addition, it was believed that the uneven or "tapered" wear observed on the cones of these bits was primarily a result of uneven wear on the lugs; the CBS-600 selected for the MK-III lugs was expected to reduce lug roller-race wear to the low levels observed on the MK-I and MK II bits, thereby reducing wear in the cone races to acceptable levels. Special nose bushings of full-hard M50 tool steel (four bits) and tungsten carbide (remaining four bits) were selected to reduce wear in the friction-pin area.

ROLLERS AND BALLS - M50 tool steel was selected because of its excellent retention of hardness at temperature; the parts were drawn back to a hardness of R_C 56 to increase toughness. Fracture-toughness tests were run on M50 roller bearings using the Terra Tek FRACTOMETER* system. Figure 16 gives the results of these tests as well as data presented previously for M50 at R_C 64, and Solar Steel used for the balls and rollers of conventional bits.

In addition, Reed Tool Company ran a "three-ball crush test", in which a stack of three balls in a tube are loaded until the center ball shatters. The ball (M50 at R_C 56, diameter of 12.7 mm or 0.500 inch) failed at 173 KN (39,000 pounds), which is at the lower limit of what is acceptable for the Solar Steel balls used on conventional bits.

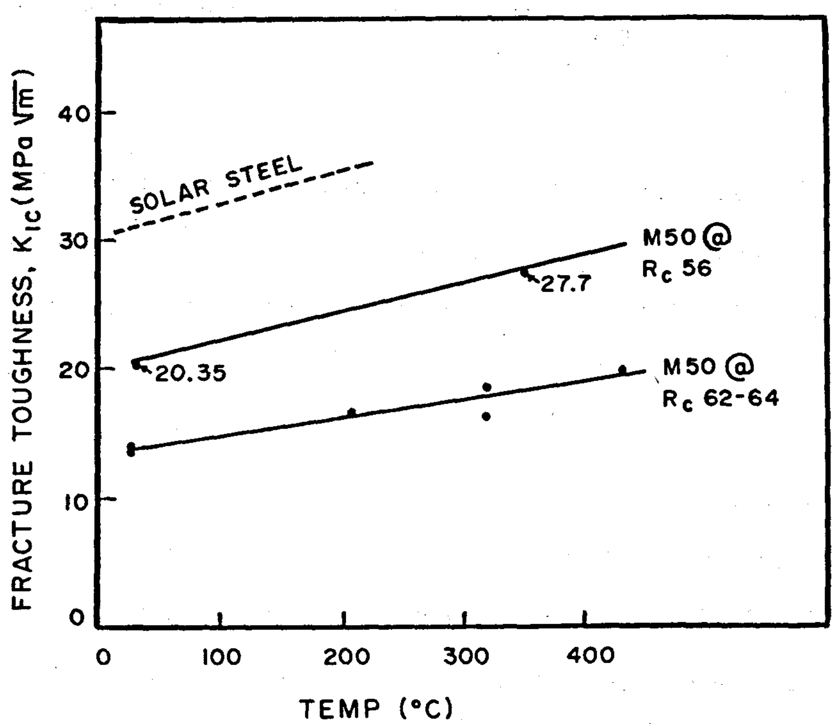

Figure 16. Fracture toughness for the roller bearing steels.

*This technique is presently being evaluated for ASTM acceptance, but a standard has not yet been issued.

INSERTS .- A harder grade of tungsten carbide was selected for the gage-cutting inserts, since gage wear is a major problem at some geothermal drilling sites. Figure 17 gives fracture-toughness values at various temperatures, and hardness values at room temperatures, for three grades of tungsten carbide.

Carboloy grade #231 is recommended by the manufacturer for drilling inserts, due to its high toughness. The data indicate, however, that grade #90 could provide 83 percent of the toughness of grade #231 at 300°C, and a significant gain of 1.2 points on the Rockwell-A hardness scale. Gage-row inserts of grade #90 may exhibit a slightly greater tendency to break, but should provide much better maintenance of hole diameter. Data are also given for Carboloy grade #248, which was used for nose-bushings for four of the eight bits; breakage of the nose bushings is not anticipated.

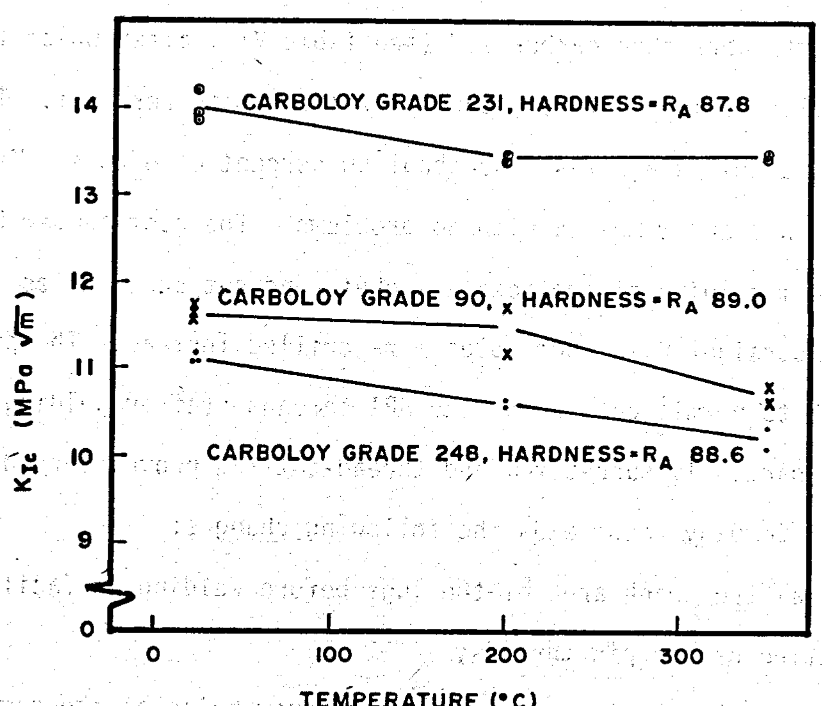

Figure 17. Fracture toughness for tungsten-carbide components.

MANUFACTURABILITY

Fabrication of the eight experimental bits has revealed several areas where manufacturing procedures need to be modified to accommodate the materials selected for the MK-III bits. The overall cost of manufacturing will probably be on the order of 10 to 30 percent higher than for conventional bits, due to the lower machinability of the CBS-600, and the smaller production quantities; specific problems are discussed below. The names and addresses of suppliers for the program are given in Appendix C.

LUGS - The CBS-600 lugs forged as easily as 8620. The post-forging hardness was about R_C 35, and Reed Tool personnel rate the machinability at about 60 percent of 8620's; most of the machining was done at this point. The parts were then carburized (see Table VI), after which the dowel holes, 120° mating surfaces, and air relief slots were cut. The machinability at this stage was also about 60 percent of 8620's. The parts were then hardened and tempered with no problems. The post-temper hardness of R_C 40 made machining of the nozzle sockets and set-screw holes too difficult and straight 0.75 inch holes were drilled instead. The pin area was drawn back to permit cutting of the API threads, (after welding), but this was only partially successful and thread-cutting proved very difficult.

Reed Tool Company recommends the following changes:

(1) Anneal the shank area of the lugs before welding to facilitate cutting of the pin threads;

(2) Machine the nozzle sockets and set screw holes at the same time as the dowel pins, 120° surfaces, and air-relief slots, *i.e.*, after carburizing, but before hardening.

CONES - No special problems were encountered since these assemblies were nearly idential to conventional cones. The grade 90 gage-row inserts pressed without difficulty, as did the tungsten carbide and M50 bushings.

ROLLERS AND BALLS - The rollers and balls manufactured previously for the MK-II bits attained the desired hardness of R_C 56, with little sample-to-sample variation. Close control of the tempering temperature is required to get the desired hardness, but such control is possible with modern heat-treating equipment. The balls for the MK-III bits attained the desired hardness with little variation, but problems arose with the rollers. The hardness tended to spread over a wide range, R_C 51 to 58, despite good control of furnace temperature; parts had to be individually checked and graded. The 450 (out of 1200) rollers actually used ranged from R_C 52 to 57 instead of the R_C 54 to 57 originally planned. The problem would appear to be with the batch of M50, or some aspect of the austenitizing procedure. A bearing manufacturer was located for the balls; the roller manufacturer could not meet program deadlines, and the work had to be completed by Terra Tek personnel and our metallurgical consultant, W. C. Leslie. Hopefully, a willing manufacturer can be located who can perfect the tempering procedure and supply M50 rollers at R_C 56 in production quantities.

FACILITIES FOR TESTING MK-III EXPERIMENTAL BITS

Testing of the MK-II bits in August, 1977, (previously described) revealed a problem with the Wellbore Simulator which had gone undetected in the five tests run previously: debris from the mild-steel pad, created by the drilling action, worked back into the bearings of the unsealed bits, causing the cones to seize. The first three bits tested in the Wellbore Simulator (two MK-I experimental, and one conventional) had escaped this problem because they were periodically removed, disassembled, cleaned, and measured for wear; the cleaning apparently prevented significant build-up of debris. The Wellbore Simulator was equipped with a magnet to trap the steel cuttings from the pad, but this was only partially successful. An ideal system would provide circulating fluid,* but the cost of such a system at the temperatures and pressures involved would have been prohibitive.

Several meetings were held to discuss modifications to the Wellbore Simulator and other alternatives which would facilitate testing of the unsealed MK-III bits. It was determined that the least expensive and most timely approach would be the construction of a new full-scale test system utilizing hot compressed air, to be used in conjunction with the Drilling Research Laboratory (Figure 18).

The Geothermal Air Drilling Test Facility (Figure 19) consists of a diesel air compressor, gas-fired heater, hot air swivel, and insulated drill collars. The drill rig provides the required bit weight** and RPM,

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

**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.

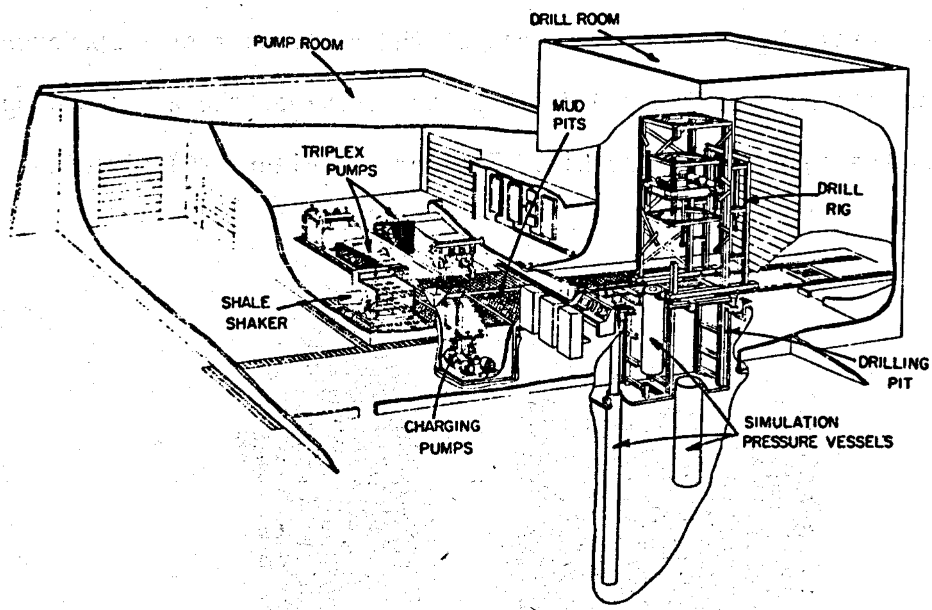

Figure 18. The Drilling Research Laboratory.

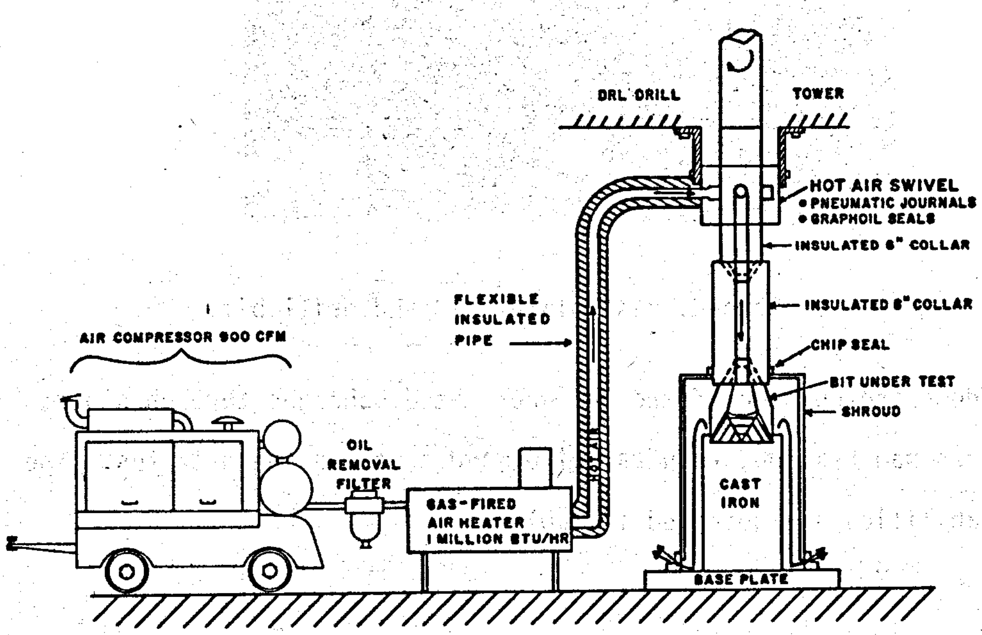

Figure 19. Geothermal Air Drilling Test Facility.

while torque, penetration, RPM, and thrust are monitored and recorded. The airflow maintains the drill bit and pad at the required test temperature; the airflow also removes the pad detritus and provides the necessary purging through the bearings of the bit. The shroud (Figure 20) directs the

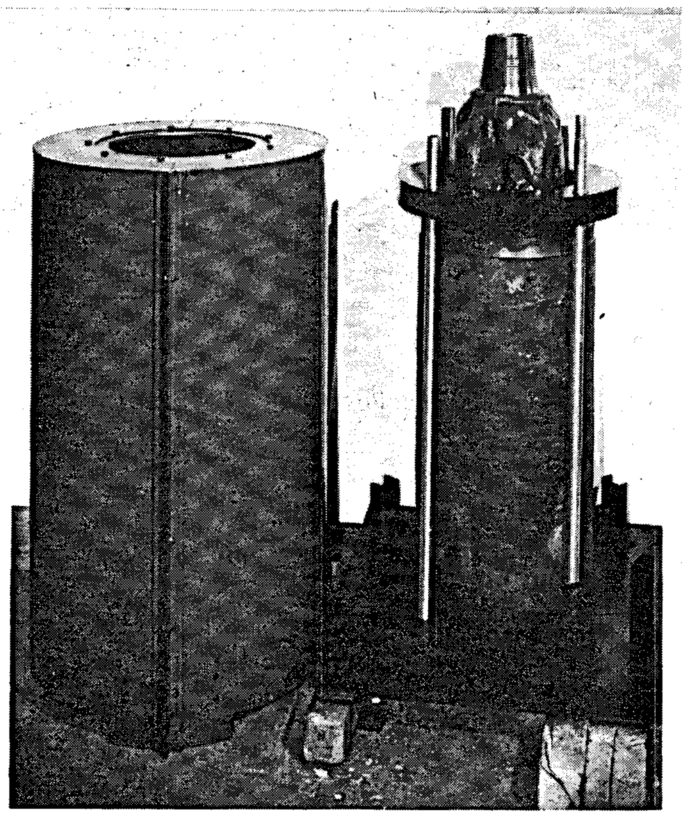

Figure 20. Shroud, base plate, pad and drill bit.

effluence down the outside of the pad where it discharges through slots; this enhances pad heating, reduces noise, and confines the detritus. The system capabilities are detailed in Table VI.

TABLE VI

CAPABILITIES FOR GEOTHERMAL AIR DRILLING TEST FACILITY

Thrust	445 KN (100,000 pounds)
Torque	4.1 KN-M (3,000 foot-pounds)
Airflow	0.35 M^3S^{-1} (750 CFM)
Temperature	426°C @ 0.24 M^3S^{-1} (800°F @ 500 CFM) 316°C @ 0.35 M^3S^{-1} (600°F @ 750 CFM)
Stroke,	0.71 M (28 inches)
Bit Size (max)	241 mm (9 1/2 inches)

The pad material selected for the MK-III bit tests was cast iron, which outlasts a rock such as granite by a factor of approximately two hundred and fifty to one, thus providing sufficient pad life for the long intervals of endurance-testing anticipated (30 to 50 hours per bit). A contour is machined into the top of each billet which is similar to the bit's normal bottomhole pattern to facilitate break-in without damaging the bit (Figure 21). The cast iron provides realistic dynamic loading of the bearing structure; rock samples would be useful for evaluation of penetration rate, specific drilling efficiency, chip formation, or wear of the cutting structure.

The facility was assembled for debugging at the exterior test station of the Drilling Research Laboratory (Figure 22). Trial runs have been completed and the system is now ready for the evaluation of the two MK-III drill bits and two conventional bits.

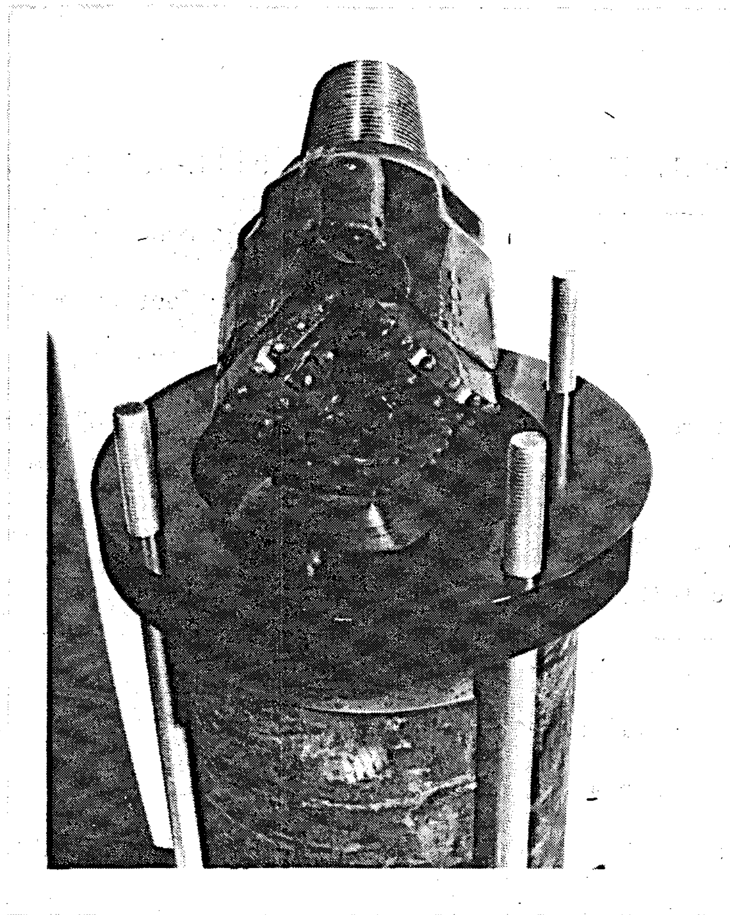

Figure 21. Cast-iron billet showing premachined contour.

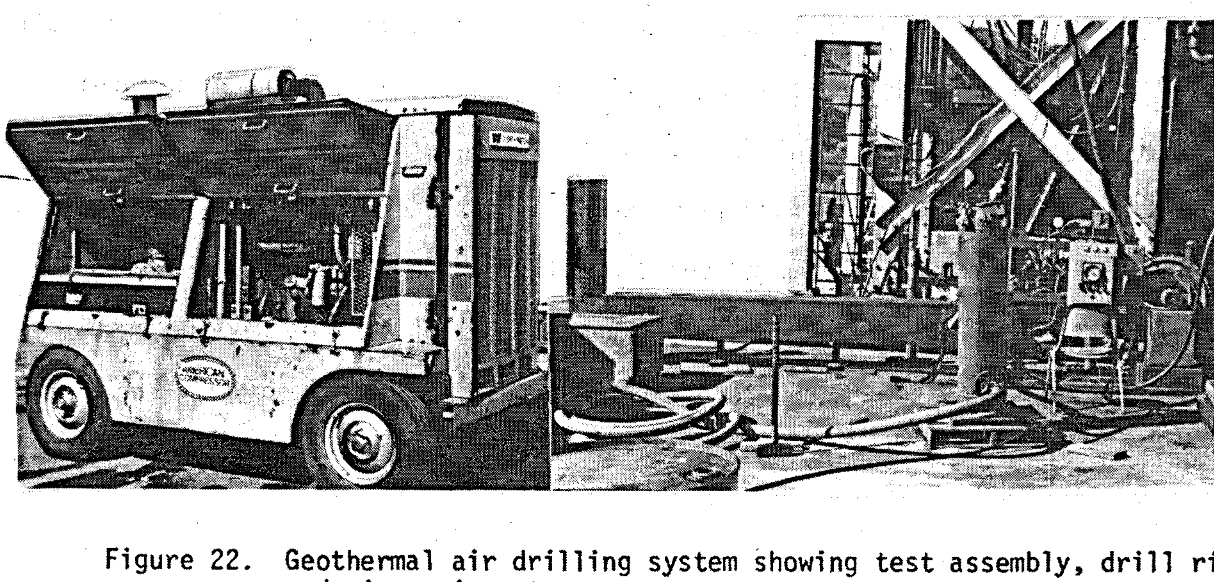

Figure 22. Geothermal air drilling system showing test assembly, drill rig and air equipment.

ADDENDUM A TO APPENDIX B

Correspondence Dealing with MK-III Experimental Bits

TerraTek

August 18, 1977

Mr. P. W. Schumacher, Jr.
Reed Tool Company-Drilling
Equipment Division
Box 2119
Houston, TX 77001

Regarding: Geothermal Bit

Dear Bill:

This letter is intended to summarize the results of our meeting on August 9th at Reed Tool, covering the geothermal drill bit program. Present were Terry Mayo, Bill Schumacher and Harry Mauzy of Reed, Bill Leslie of the University of Michigan, and Bob Hendrickson of Terra Tek. Dewey Thiessen sat in on part of the afternoon session. The major topic of discussion was the selection of materials and procedures for the eight third-generation geothermal drill bits which will be built by Reed. The bits are to be similar to Reed's Y73 JA, in the 8-3/4" size.

I. Lugs

a) Material: Timken CBS-600 steel. To be obtained by Terra Tek; at least 60 feet of 3-1/2 inch RCS stock will be supplied ready for forging. I will relay an expected delivery date to Reed as soon as possible. We are trying to better the date of October 10 which Timken gave us yesterday.

b) Heat treating: Carburize at 1750°F such that 40 pt. of carbon is obtained at a depth of 0.070", oil-quench. Austenitize at 1550°F, oil-quench. Double-temper at 600°F.

II. Cones

a) Material: AISI #4820. Bill has obtained at least 24 cones for use in the geothermal bit program. These are in the semi-finished condition: holes have been drilled, but no inserts, button nor bushing have been pressed in, and finish-grinding has not yet been done.

b) Pilot-Pin Bushing

i) Four sets of cones will have tungsten-carbide bushings of G.E. Carballoy #248. Reed will supply Terra Tek with a drawing

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of this bushing, and Terra Tek will purchase the bushings. Bill Leslie has contacted Carballoy in Detroit and received an estimated delivery of 9 to 12 weeks ARO. Reed will apply a hard-facing material of their choice to the pilot-pins of the lugs to be run in these four bits. The use of a tungsten carbide bushing for the pilot-pins is patented by Reed.

ii) Four sets of cones will utilize a pressed-in bushing of a tool steel which is to be selected by Bill Leslie (possibly M50). Reed will supply a drawing of this part to Terra Tek, who will obtain the required steel and fabricate the parts. The finished bushings will then be sent to Reed for final assembly. The lugs to be run against these bushings will be hard-faced by Reed with a material to be selected by Bill Leslie. This will probably be group 4A Stellite.

c) Cones will have the standard M80 button pressed into the nose.

d) Drilling Inserts

i) Gage row: To be of hardest practical carbide alloy such as G.E. Carballoy #248 or #90, hemispherical.

ii) All other inserts: Standard inserts used in the Y73 JA bit.

III. Bearings, Rollers and Balls

a) To be M50 bearing steel, heat treated to Rockwell R_C 54-58. This is pending favorable results of hot fracture-toughness tests, to be performed the first week in September by Terra Tek. Terra Tek will supply the finished parts to Reed for assembly.

IV. Assembly

a) Reed will identify all parts with stamped numbers or letters. Terra Tek would prefer that the four carbide-bushing bits be stamped I, J, K, and L, and the four tool-steel-bushing bits M, N, O, and P.

b) Lugs will be welded together.

c) Ball insertion track will permit free removal of balls. Ball plug to be welded with minimum necessary amount of weld.

The tentative October 10th delivery date, coupled with Reed's required six months, gives us a bit completion date of April 10th, 1978; program funding ends on May 19th, 1978. We obviously need to press our suppliers to better their delivery dates wherever possible. Anything that can be done to speed up this schedule should be given serious consideration.

I am tentatively scheduling a program review meeting for Wednesday, September 7th at the Drilling Research Laboratory. A letter will follow shortly with firm details.

Sincerely,

Robert R Hendrickson

Robert R. Hendrickson
Project Engineer

RRH/jlg

cc: Dewey Thiessen, Reed Tool Company
Terry Mayo, Reed Tool Company
Harry Mauzy, Reed Tool Company
Bill Leslie, University of Michigan
S. J. Green, Terra Tek
A. H. Jones, Terra Tek
L. M. Barker, Terra Tek
R. W. Winzenried, Terra Tek
B. J. Sakashita, Terra Tek

TerraTek

September 20, 1977

Mr. Jon H. Barnette
Drilling Research Division
Geothermal Energy Technology Dept.
Sandia Laboratories
P.O. Box 5800
Albuquerque, NM 87115

Dear Jon:

This letter is intended to summarize the program review meeting on the ERDA/DGE Geothermal Drill Bit contract, E(10-1)1546, held at Terra Tek on September 7th, 1977, and should also serve as this month's progress letter.

Attendees:

Jon H. Barnette	Sandia Laboratories
Harry L. Mauzy	Reed Tool Company
Larry Matson	Maurer Engineering
Lynn M. Barker	Terra Tek, Inc.
Robert R. Hendrickson	Terra Tek, Inc.
Bruce J. Sakashita	Terra Tek, Inc.
Richard W. Winzenried	Terra Tek, Inc.
Prof. William C. Leslie	University of Michigan, Consultant to Terra Tek
Paul J. Garmus	The Timken Co. (non-participating)

The meeting opened with Jon Barnette giving a brief overview of Sandia's role as contract monitor for ERDA/DGE. I then reviewed the progress made during the year on the major tasks of the contract.

Dick Winzenried gave a detailed analysis of the drill-bit tests run in the geothermal wellbore simulator. These included the MK II bits run in August, and two conventional bits run last April. The two bits tested in April were run at intermediate geothermal temperatures of 300°F and 450°F, at loads of 20,000# for two hours and 25,000# for two hours. The bit tested at 450°F experienced severe wear but did complete the test sequence. The bit run at 300°F completed the 2 hours at 20,000# but locked up after 40 minutes at 25,000#. Upon analysis, it was discovered that the wall between the ball race and roller race had broken, and the chips had jammed the rollers, causing the cone to seize. This was most likely caused by excessive axial force on the ball race, since the back (outside) edge of the

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cutter cone is unsupported by the steel pad, but would receive some support from the outer wall of the hole in an actual drilling situation. Reed Tool said that this raceway breakage was one of the more common drill bit failure modes. The next test sequence was run in August, and consisted of two MK II research bits and one conventional bit. To avoid the raceway breakage problem, these bits were given a one hour progressive break-in sequence. This was intended to wear a pattern into the pad which would provide more support for the cone, and hopefully alleviate some of the axial thrust on the ball raceways. The first bit tested was a MK II experimental which locked up after two hours at 25,000# at 316°C. It was originally hoped that each bit could be run for six hours. The second bit run was a conventional unit; in view of the lockup of the first bit, the load was reduced to 20,000#. This bit was run five hours, but examination of the bit and the torque graph indicated that intermittent locking of the cones may have been taking place for the last two hours of the test. The final test was the second MK II bit, which seized after one hour and 45 minutes at 20,000#. It is now believed that these premature failures were caused by the lack of circulating fluid in the wellbore simulator, which allowed internally generated wear debris to jam in the roller raceways. Proposed modifications to the tester are covered later in this report. Wear analysis of the three bits revealed results similar to the MK I tests last November; roughly one-fifth to one-tenth as much wear on the research bit as on the conventional bit.

Bill Leslie reviewed the materials selected for the third generation of research drill bits. These were decided upon at a meeting between Reed Tool and Terra Tek on August 9th at Reed Tool in Houston. This subject is best summarized by my letter to Bill Schumacher dated August 18th (copy attached), since we are holding almost exactly to those selections. The most significant decision was the selection of Timken CBS-600 steel for the lug material. This material was selected after a detailed analysis of the hydrogen sulfide embrittlement problem by Prof. Leslie and myself; I have attached a copy of our letter to Cliff Carwile, dated September 7th, which details our findings. This steel should be capable of supplying the hot hardness, fracture toughness, and resistance to hydrogen embrittlement that is required.

Lynn Barker reviewed the fracture toughness program at Terra Tek and outlined his proposed tests for the materials to be used on the MK III drill bits. These include fracture toughness tests on the M50 roller bearings, the tungsten carbide for the gage row inserts, the carbide for the other drilling inserts, and the carbide for the pilot bushing. Fracture toughness tests are also planned for the CBS-600 alloy which will be used for the MK III lugs and 8620 steel which is used for conventional lugs. Due to their high toughness, these tests may not be entirely valid as a true measure of K_{IC}, but should provide good data on the relative toughness of the two steels.

Dick Winzenried reviewed the current status of the seal tester. The most significant development came early this summer when Dick perfected a technique for detection of seal failure. The tester continues to operate reliably, and over 140 seal tests have been run to date. The results of 17 "test-to-failure" seal tests were discussed. These tests were run at 200°C, and show Buna-N to be slightly better than Viton, whereas earlier tests at 235°C had shown Viton to have a slight advantage over Buna-N. Since this temperature region is still inadequate for geothermal applications, it was agreed that future testing should move almost exclusively to the heterogeneous sealing systems. (Some testing will be done on Kalrez and paralene-coated seals.)

Larry Matson of Maurer discussed the current status of some of the heterogeneous sealing concepts, and outlined plans for new seals. Terra Tek will continue work on materials for its "Spider" face seal, testing of the Sealol metal bellows face seal, and possible testing of the Parker "Geopak" seal. The Parker "Geopak" will utilize a "Vespel" plastic (polyamid-imid) lip seal driven by a metal spring; Parker is experiencing delays with their molding equipment, however, and the "Geopak" is not the first seal in line for fabrication once production is put "on line".

R. Hendrickson reviewed the geothermal lubricant tester. This is a block-and-ring tester similar to the Alpha LFW-1, but designed for service to 800°F. It is exactly as described in the proposal for this year's contract. At the present time there is very little information on lubricant performance at temperatures much above 400°F, and very little consensus from lubricant experts on how extensive a problem H.T. lubrication will be. Completion and operation of the tester is scheduled for November.

The final discussion centered around proposed modification to the geothermal wellbore simulator. Design changes had been initiated prior to the MK II bit tests to increase the simulator's capacity from 6-3/4" out to 8-3/4" so that two of the MK III bits could be lab-tested prior to taking the remaining six to the Geysers for testing. However, the MK II bit tests, with their frequent cone lockups, indicated that some form of fluid circulation is needed to flush wear particles from the bit. This is a formidable engineering task which we are now working on. The most promising solution discussed so far would utilize a positive-displacement pump inside the vessel (such as a gear pump) driven by the drill shaft.

The pump would draw water in through a porous bronze filter and down through the lugs to provide the flushing action. This, coupled with the one hour wear-in procedure, should allow long duration geothermal well-bore simulation tests.

The following conclusions and agreements were reached prior to the close of the meeting.

1. Reed Tool would provide Bill Leslie with drawings of the pilot-pin bushing for both the tungsten carbide and the tool-steel versions of the MK III bits. (Bill informs me these have been received, and he is proceeding with the purchase of thirty of each type.)

2. Harry Mauzy would look into having Reed do a complete inspection on all drill bits to be run in the field tests: both the research type and conventional units. (He has since informed me that Reed would inspect, i.e. measure, the research bits, but that they need a firm order for the conventional bits from Union Oil before considering inspection of those.)

3. Bill Leslie will procure three types of carbides, probably G.E. #'s 248, 90 and 231 for fracture toughness testing by Lynn Barker of Terra Tek. These are the grades to be used in the gage row inserts, pilot bushing, and other rows of drilling inserts.

4. Larry Matson will do a detailed investigation into the face seals currently on the market, with the goal of adapting them for high-temperature service. Larry also agreed to get some exact specifications from Reed on the maximum amount of space that can be usurped from the rest of the drill bit, should the need arise.

5. Dick Winzenried agreed to pursue modifications to the seal tester which would include a system for bearing purge action, as well as enlargement to the 8-3/4" size.

6. Lynn Barker agreed to do fracture toughness tests at temperature on three samples of tungsten carbide. In addition, Lynn agreed to attempt a measurement of the core toughness of the CBS-600 steel, providing that Bill Leslie could provide three samples of at least 2" diameter x 3" long. Bill also agreed to prepare the samples to the proper heat treat in his lab.

7. Jon Barnette requested that Terra Tek provide him with a monthly progress letter rather than a bimonthly report. (I have discussed this with Sid Green, and we will now provide a monthly letter.)

Sincerely,

Robert R. Hendrickson/jlg

Robert R. Hendrickson
Project Engineer

RRH/jlg

Enclosures: Letter to P. W. Schumacher, 8-18-77
Letter to C. Carwile, 9-7-77

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ADDENDUM B TO APPENDIX B

Letter to ERDA Dealing With
Hydrogen Sulfide Embrittlement

TerraTek

September 7, 1977

Mr. Clifton Carwile
Project Manager
Exploration Technology Branch
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20 Massachusetts Ave., N.W.
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Subject: Hydrogen Sulfide Embrittlement

Dear Cliff:

Prior to selecting the steels for the third-generation drill bits, a thorough investigation was made into the nature of hydrogen embrittlement as it relates to oilfield products in general, and geothermal bits in particular. This was in response to questions raised by Bob Reeber of ERDA, and several people from the drilling industry. We talked with Prof. A. R. Troiano of Case Western Reserve, and also with key people in the metallurgical departments of three of the bit manufacturers.

We have studied two recent comprehensive reviews of hydrogen embrittlement in steels.[1,2] Although it must be clearly recognized that no high-strength steel is immune to hydrogen embrittlement, we have selected steels that have no history of such embrittlement when used in drill bits.

The Basic Problem

There is no general agreement in the metallurgical community as to the exact mechanism or mechanisms of hydrogen embrittlement. It is, however, generally agreed that the process is greatly accelerated if the H_2S is dissolved in water. Since this allows the hydrogen ions to dissociate from the sulphur, the hydrogen ions or "atomic hydrogen" can then freely penetrate

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1. C. S. Carter and M. V. Hyatt, "Review of Stress-Corrosion Cracking in Low-Alloy and Low-Strength Steels," Proceedings Firming Conf., Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, June, 1973.

2. I. M. Bernstein and A. W. Thompson, "Effect of Metallurgical Variables on Environmental Fracture of Steels," Int. Met. Rev., 21, p. 269, 1976.

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the crystal lattice of the steel. One theory holds that the atomic hydrogen collects in micro-voids within the steel, where it recombines to form diatomic hydrogen, i.e. H_2 gas, thereby producing a localized stress and perhaps initiating a crack. The embrittlement problem increases as the stress on the steel increases, and is known to be worse in steels lacking in fracture toughness.

Prevention

In oil and gas well drilling, H_2S is a frequent problem which is usually controlled with mud additives. According to John Day of Maurer/MudTech, the usual choice is a mixture of zinc chromate or sodium chromate in combination with zinc oxide or zinc carbonate. Typical concentrations of these additives are about 500 ppm by weight. This approach points up the fact that there is no effective way to create a barrier to hydrogen. There is no known electroplate, dip, impregnation or other coating that will stop hydrogen diffusion and which is also reasonably resistant to shock and abrasion; glass and thick rubber coatings provide some protection, for example. Hydrogen embrittlement can be minimized by controlling metallurgical variables. The residual stress pattern induced by carburizing results in parts which are less susceptible to embrittlement: the case is in compression, whereas the embrittlement crack usually originates in an area of tension. Fine grain size and a tempered martensite structure are beneficial; these are always present in conventional drill bit steels.

Coating amines may be used as additives when drilling with mud or air. In mud, the coating action of the amines provides some protection from hydrogen diffusion to the drill pipe and casing. When used with air drilling, its primary function is to surround the abrasive cuttings, thereby reducing abrasion of the tool joints and casing by the cuttings as they leave the well. For example, a Union Oil product known as Unisteam is injected into the drilling air at the Geysers geothermal wells. According to Delbert Pyle of Union, Unisteam does contain amines and should provide some H_2S protection for the drill pipe and casing, in addition to reducing abrasion. However, amines cannot provide significant protection for the drill bit due to the constant scraping, whether drilling with mud or air.

Mitigating Factors

Although true geothermal drilling muds are not yet available, the MudTech division of Maurer Engineering is developing this technology. Larry Reamont, head of the MudTech group, states that zinc chromate, sodium chromate, zinc oxide and zinc carbonate chemistry should work well at geothermal temperatures for the neutralization of hydrogen sulfide.

The primary concern, therefore, is the air-drilled geothermal well. There are two factors here that work to our advantage. First, the drill bit is only exposed to steam as it passes through a steam entry point, or when tripping, since the drilling air provides a constant purging action. Secondly, the H_2S embrittlement problem usually decreases with increased temperature (although it is uncertain as to whether this is due to the greater mobility of hydrogen, or to an increase in the fracture toughness of the steel). Brittle failure of drill bits at the Geysers has been almost non-existent, according to Kelsey Lumen of Union Geothermal.

Materials Selection

The bit components exposed to the wellbore fluids are the cones and lugs. Of these two, the lugs are generally more prone to cracking. The material selected for the MK III drill bit cones is 4820 steel. Since this material has been used extensively at the Geysers, no problems are expected from the cones. The lug material selection was more critical, since greater retained hardness is needed at temperature in order to reduce bearing wear. Thus, the material selected had to have fracture toughness equal to or greater than that of the conventional 8620 steel. The material selected is Timken CBS-600, which, according to C. F. Jatzcak of Timken, should meet these goals. The CBS-600 should allow a retained case hardness of R_c58 at 600°F, but with a core hardness in the area of R_c30. The lug steel used on the MK I and MK II drill bits, H13 tool steel, could not provide nearly as wide a core/case differential. Vasco X2CVM carburizing steel (also considered) had hardnesses of about R_c58 case/R_c50 core, although its retained hardness is better than CBS-600 at 800°F. The core hardness of 8620 steel is about R_c25 at room temperature. Unfortunately, it is difficult to make fracture toughness measurements on steels as tough as 8620 or CBS-600; the required sample size is too large. Lynn Barker of Terra Tek has indicated that he may be able to devise a test that can at least provide relative fracture toughness measurements for 8620 versus CBS-600, at temperature.

We therefore conclude that the MK III drill bits should be no more susceptible to embrittlement failure than conventional bits, when run at the Geysers at typical loads of 25,000#-35,000#. It is hoped that fracture toughness data, to be generated at Terra Tek, will show the toughness of CBS-600 relative to 8620 steel. If CBS-600 is tougher in the temperature range of interest, we would then probably recommend that the bit load be increased to the neighborhood of 40-45,000 pounds in order to attain the higher penetration rates that these bits are capable of, as exhibited in non-geothermal applications.

Sincerely,

Robert R Hendrickson William C Leslie

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ADDENDUM C TO APPENDIX B

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