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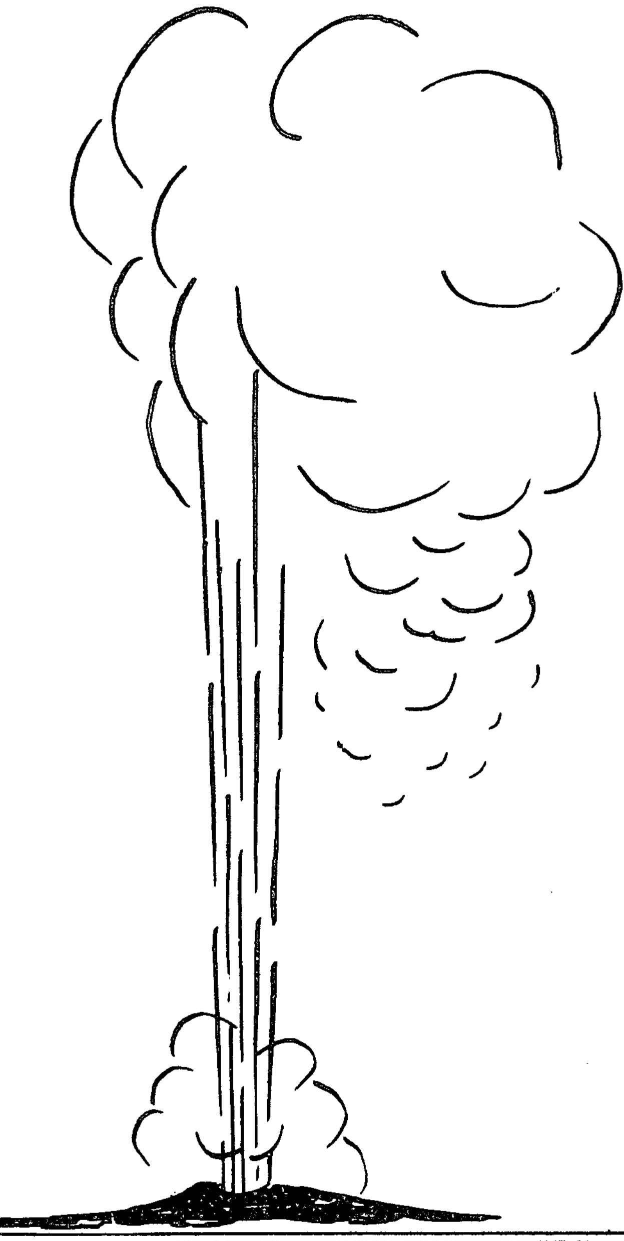

SUPPORT RESEARCH FOR DEVELOPMENT OF IMPROVED GEOTHERMAL DRILL BITS

Annual Report

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

July 1978

Work Performed Under Contract No. EY-76-C-07-1546

Terra Tek, Inc.
Salt Lake City, Utah

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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Submitted to

Department of Energy
Division of Geothermal Energy
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Submitted by

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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.

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INTRODUCTION

The work reported herein is a continuation of the program initiated under DOE Contract E(10-1)-1546* entitled "Program to Design and Experimentally Test an Improved Geothermal Bit"; the program is now DOE Contract EG-76-C-1546*. The objective of the program has been to accelerate the commercial availability of a rolling cutter drill bit for geothermal applications. Data and experimental tests needed to develop a bit suited to the harsh thermal, abrasive, and chemical environment of the more problematic geothermal wells, including those drilled with air, have been obtained. Efforts were directed at the improvement of both the sealed (lubricated) and unsealed types of bits. The unsealed bit effort included determination of the rationale for materials selection, the selection of steels for the bit body, cutters, and bearings, the selection of tungsten carbide alloys for the friction bearing, and a preliminary investigation of optimized tungsten carbide drilling inserts. Bits built** with the new materials were tested under simulated wellbore conditions. The sealed bit effort provided for the evaluation of candidate high temperature seals and lubricants, utilizing two specially developed test apparatus which simulate the conditions found in a sealed bit operating in a geothermal wellbore.

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*This has been a joint program with Maurer Engineering (MEI); the MEI effort has included the conducting of patent surveys on seals, lubrication systems, bearings and inserts (References 1 and 11). Assistance was also provided on mechanical seal designs (Reference 13), and the solicitation of high-temperature lubricants from manufacturers.

**All full-scale bits were built by Reed Tool Company at no cost to the program. Sixteen bits have been built by Reed using their standard assembly-line processes.

Phase I of the program was devoted largely to (1) the study of the goethermal environment and the failure mechanisms of existing geothermal drill bits, (2) the design and construction of separate facilities for testing both drill-bit seals and full-scale drill bits under simulated geothermal drilling conditions, and (3) fabrication of the MK-I research drill bits from high-temperature steels, and testing in the geothermal drill-bit test facility. The work accomplished in Phase I is reported in References 1 through 9.

In Phase II, the first generation experimental bits were tested in the geothermal drill-bit test facility. Test results indicated that hardness retention at temperature, but not at the expense of fracture toughness, was a primary requirement for geothermal bit bearings. Materials selections for the MK-II bit were made based on these results. Also in Phase II, effort was directed at the screening of elastomers for use as a high-temperature seal for sealed bits. References 10 through 13 report the work performed in Phase II.

This report summarizes the work on Phase III, encompassing the period from May 18, 1977, to May 19, 1978. There were two major tasks in Phase III:

- Material selection, fabrication and testing of MK-III bits;
- Seal and lubricant evaluation.

Work performed in Phase III is described in more detail on the following pages.

TASK I - UNSEALED DRILL BIT DEVELOPMENT

MK-III Drill Bits

Two second-generation experimental bits (MK-II bits developed during Phase II) were completed and run in the Geothermal Wellbore Simulator during this reporting period. The results of these drilling tests will be detailed below as part of the relevant efforts preceding materials selection and construction of the MK-III bits during Phase III.

In Phase I it was determined that the predominant bit failure modes at the problematic drilling sites (those involving air drilling into hard, abrasive formations) were excessive bearing wear and loss of "gage", *i.e.*, bit diameter. In order to reduce bearing wear, the first generation (MK-I) experimental drill bits were fabricated from steels known to retain hardness and strength at elevated temperatures. Two of these bits were subjected to full-load drilling tests at 317°C in the Drilling Research Laboratory, utilizing the Geothermal Wellbore Simulator. Wear measurements on internal bearing surfaces revealed only one-fifth to one-tenth as much wear as was measured on a conventional Reed M83-JA bit, run under the same conditions. The MK-I bits did suffer from cracking of the cutters.

Fracture toughness tests performed on the steels used in conventional bits and the MK-I experimental bits over the temperature range of 20°C to 400°C showed that toughness levels for the conventional bit steels were substantially higher than those used in the MK-I bits.

Materials selections for the MK-II bits were made during Phase II and were based on results of the MK-I laboratory drilling tests, material hardness and fracture-toughness determinations. The data indicated a need for substantial improvements in toughness, especially for the cutters, rollers, and balls. The minimal wear experienced by the MK-I bearing components demonstrated the importance of retained hot-hardness, but also suggested that some of this hardness could be "traded off" for more toughness. The manufacturability of candidate steels was discussed with steel suppliers and Reed Tool Company personnel, since the bit components would have to be forged, heat treated and machined utilizing existing factory facilities. The latter is the dominant factor for determining success of accelerated commercialization, as well as being a near-term necessity for fabricating experimental bits. The materials used in the MK-II bits were as follows:

Lugs:	H-13 Tool Steel
Cutters:	Vasco X2 CVM
Roller Bearings:	M 50 Tool Steel @ R_C 56
Ball Bearings:	M 50 Tool Steel @ R_C 56
Bushings:	None
Buttons:	None
Inserts:	Tungsten Carbide, Carboloy grade 231
Design Configuration:	Reed Y73 JA 6-3/4 inch

The composition of these steels, and others discussed herein, are given in Table I.

Difficulty was encountered in fabricating the cutter cones from Teledyne-Vasco X2 CVM tool steel. The original plan called for case-carburizing and heat treating to obtain a surface hardness of about R_C 56, while obtaining R_C 40 at depth. The actual values were R_C 57-58 in the

TABLE I

NOMINAL STEEL COMPOSITIONS

Steel	Composition (%)							
	C	Cr	Mn	Mo	Ni	Si	V	W
AISI #8620	0.20	0.50	0.78	0.20	0.55	0.27	--	--
AISI #4820	0.20	--	0.60	0.25	3.50	0.27	--	--
AISI S2 (Solar Steel)	0.50	--	0.40	0.5	--	1.00	--	--
AISI M-50	0.80	4.00	0.25	4.50	0.10	0.25	1.00	--
AISI H-13	0.37	5.25	0.35	1.30	--	1.00	1.00	--
Vasco MA	0.51	4.50	--	2.75	--	0.22	1.00	2.00
Vasco X2	0.22	5.20	0.25	1.30	0.06	1.00	0.40	1.35
Vasco X2 Mod.	0.13	5.20	0.25	1.30	0.06	1.00	0.40	1.35
CBS-600	0.2	1.46	0.55	1.0	--	1.1	--	--
CBS-1000M	0.13	1.05	0.50	4.5	3.0	0.50	--	--

carburized areas, and R_C 50 in the body, which was too hard to permit drilling holes for the tungsten-carbide inserts. Two subsequent tempering operations reduced the core hardness to R_C 40, allowing the drilling of insert holes; however, in the heat treatment, the hardness of the carburized areas was reduced to R_C 47. Note that these cutters were fabricated without the bushing and button that are press-fit into the friction-pin area of conventional cones, since the Vasco X2 CVM (at R_C 57-58) should have provided adequate wear resistance for the load-bearing surfaces. Hence, the deficient (R_C 47) case hardness could be expected to cause the greatest problem in the friction-pin area.

The roller bearings were drawn back to R_C 56 from the normal hardness of R_C 64 in order to increase toughness; fracture toughness data on M50 at R_C 56 are presented in another section of this report.

Lugs for the MK-II bits were identical to those of the MK-I bits, since the data suggested adequate toughness for H-13, although toughness values were somewhat less than for AISI 8620, used on conventional lugs.

Two MK-II bits (designated G and H) were fabricated in the take-apart configuration by Reed Tool Company, for evaluation in the Geothermal Wellbore Simulator. These bits, like the MK-I bits, were similar in geometry to the Reed 6-3/4 inch M83-JA hard-formation bit.

Laboratory Drilling Tests on MK-II Bits

The two MK-II bits, G and H, and one conventional bit of the take-apart type, were run in the Drilling Research Laboratory in August, 1977. The Geothermal Wellbore Simulator was modified for these tests to permit rapid replacement of the mild steel drill pad; a new pad was used for each of the three bits. Drilling tests were run with water at 27.6 MPa (4,000 psi) and 316°C in the Wellbore Simulator; each bit was scheduled to run for one hour at 22 KN (5,000 pounds) and six hours at 111 KN (25,000 pounds). The one-hour break-in period wore a pattern in the steel pad providing more uniform support for the cones, thus alleviating some of the axial thrust on the ball races; in field drilling situations this support is provided by the hole wall. The break-in was considered essential because tests run on conventional bits "E" and "F", which were run at full load without the pad break-in period, experienced breakage of the ball races on the lugs; these tests are described in the Phase I annual report[13].

MK-II Bit "G" - The first bit tested was MK-II bit "G", which completed the break-in period and ran for two hours at 111 KN (25,000 pounds), at which time the torque increased suddenly and the test was terminated. Examination of the bit revealed that all three cones had "locked up" and skidded on the pad (Figure 1). The cones will normally leave a regular pattern of undulations in the pad, rather than the smooth grooves shown in Figure 1.

The lug/cone assemblies were soaked in solvent for several hours to loosen the ball bearings. Upon removal of the cones, the rollers were found to be immobile in the lug raceway due to the intrusion of fine steel particles. Wear of the internal components was very slight; surfaces of the friction pin, roller races, rollers and balls were smooth (Figure 2). The ball-bearing races on the lugs exhibited slight "orange-peel" effect. The low (R_C 47) hardness in the carburized areas of the cones (discussed previously) did not cause a major wear problem at the friction pin as was originally feared. Comparative wear measurements for all three bits are given in Table II.

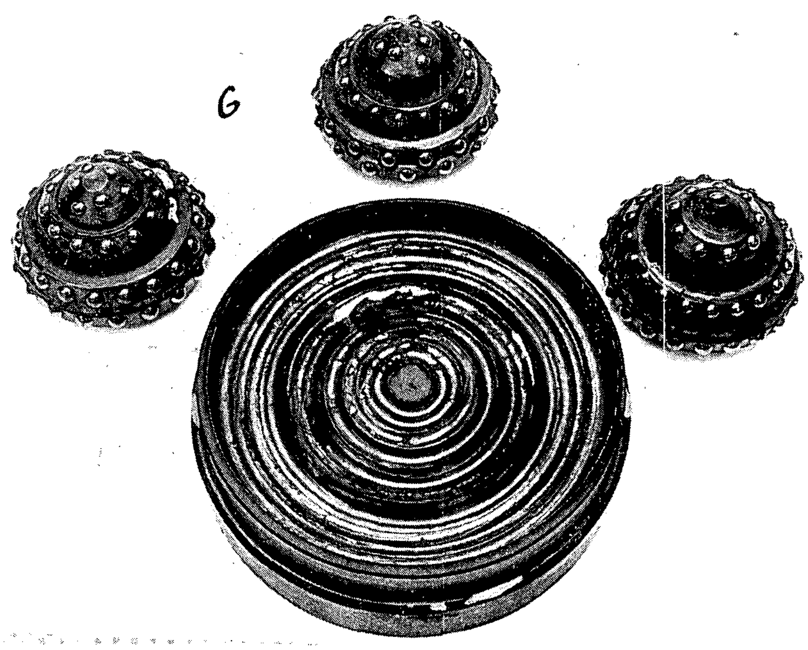

Figure 1. Pad and cones from MK-II bit "G".

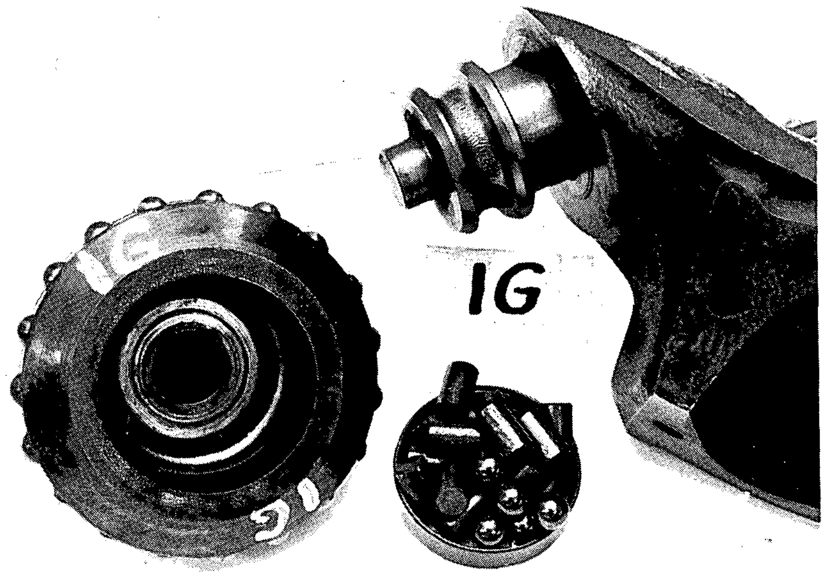

Figure 2. Cone, lug, rollers and balls of MK-II "G", lug #1, showing minimal wear.

The lack of any significant internal wear strongly suggested that the foreign matter responsible for the cone seizure came from outside the bit. This was possible since the bits were of the unsealed type and no circulating fluid was provided in the Wellbore Simulator. In a normal drilling situation, some of the drilling fluid is diverted by internal passageways to the ball races and out through the roller races; this flushing action keeps the detritus out of the bearings. The Wellbore Simulator was not designed to provide a flow of drilling fluid due to the technical difficulty of such a system (although a method of detritus removal was included and is discussed in another section).

A brittle failure was experienced on one of the three lugs of bit "G" (Figure 3), which was discovered while removing the bit from the drill pipe.

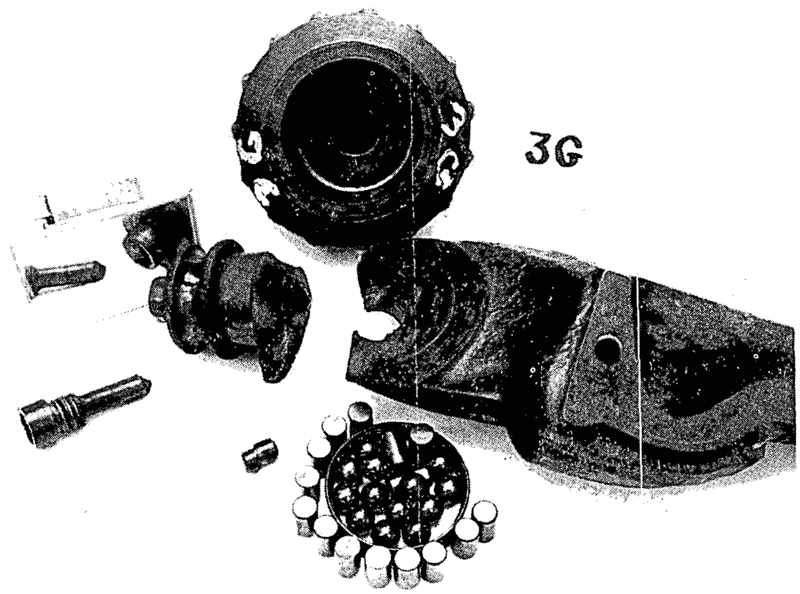

Figure 3. MK-II bit "G", lug #3 components, including broken lug.

The lug may have cracked during drilling or during the skidding. Alternately, the crack could have been caused by "hydrogen embrittlement", *i.e.*, stress-corrosion cracking (see Appendix B) during cool-down of the bit, and not during the drilling; this would explain why the parts had not totally separated during rotation. Both scenarios are indicative of insufficient toughness for the H-13 tool-steel lugs.

Conventional Bit "A" - The second bit to be tested was conventional bit "A"; in view of the lock-up problem experienced on bit "G", a lower "full load" value was selected.* Bit "A" completed the one-hour break-in period and ran for an additional five hours and sixteen minutes at 89 KN (20,000 pounds), at which time the test was stopped due to high erratic torque data.

*It was then believed that bit "G" had seized due to breakage of the ball-races on the lugs, caused by excessive axial loading of the cones.

Examination of the bit and pad revealed locked cones and extensive wear caused by skidding. The extent of the skidding wear (Figure 4) indicated that at least one of the cones had locked up much earlier. Subsequent examination of the torque graph suggested that cones were skidding intermittently between two and one-half and three hours into the test and had totally locked up by three hours.

Disassembly revealed detritus intrusion, and subsequent jamming of the roller race, as described for bit "G"; difficulty was experienced in removal of the cones due to the steel detritus particles; some of the particles were slivers over one quarter inch in length. On lug #3 of bit

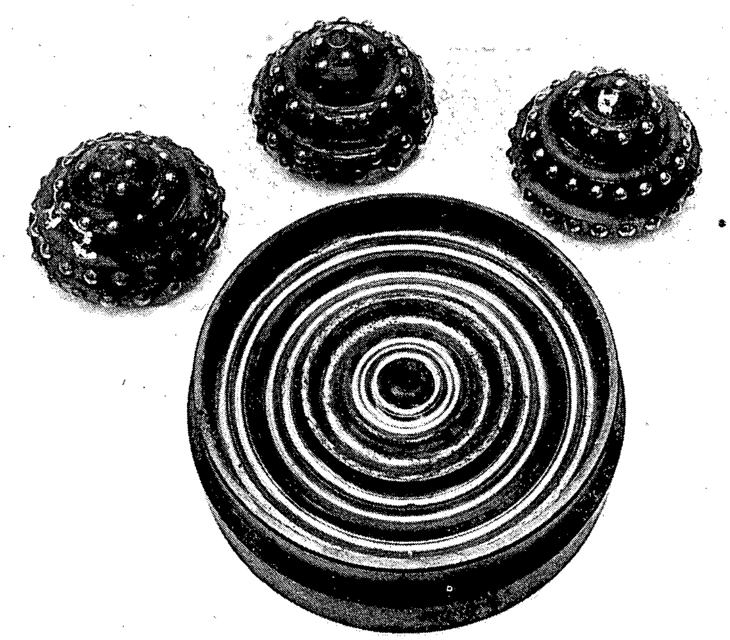

Figure 4. Pad and cones for conventional bit "A".

"A", the rollers jammed severely (Figure 5), and remained on the lug despite the soaking in solvent. Flats on the rollers indicate that at one time the cone slid over the rollers. The balls and ball races exhibited more surface damage than the MK-II bits; detritus was heavily embedded in the cone ball races (Figure 6).

MK-II Bit "H" - The third bit tested was MK-II experimental bit "H"; this bit completed the one-hour break-in period and was run for an additional one hour and forty minutes at 89 KN (20,000 pounds). The test was terminated when the torque increased and became erratic, as occurred with the previous two tests. The smooth gouges in the pad indicate skidding (Figure 7), but the lack of significant damage to the cones suggests that the cones had not skidded very long, and that the erratic torque data does, in fact, indicate cone lock-up. Examination of the bearing surfaces (Figure 8) revealed almost no wear, including the friction-pin areas of the cones, discussed previously; some "orange-peel" wear was evident on the lug ball races. Disassembly was difficult due to the steel detritus particles, as with the previous two bits; nearly all of this foreign matter was removed from the parts shown in Figure 8, although some remains in the ball race on the cone.

Baseline measurements were made prior to the drilling tests described above. At the completion of the tests, each bit was disassembled, cleaned, and all bearing surfaces were measured at several points to determine minimum and maximum wear; for clarity Table II lists only the maximum values.

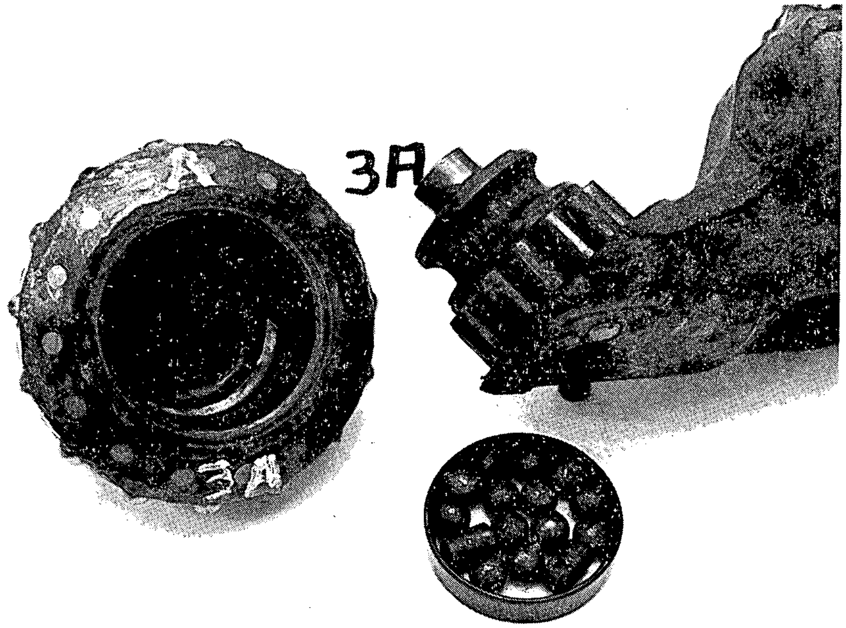

Figure 5. Cone, lug and seized rollers of conventional bit "A", lug #3.

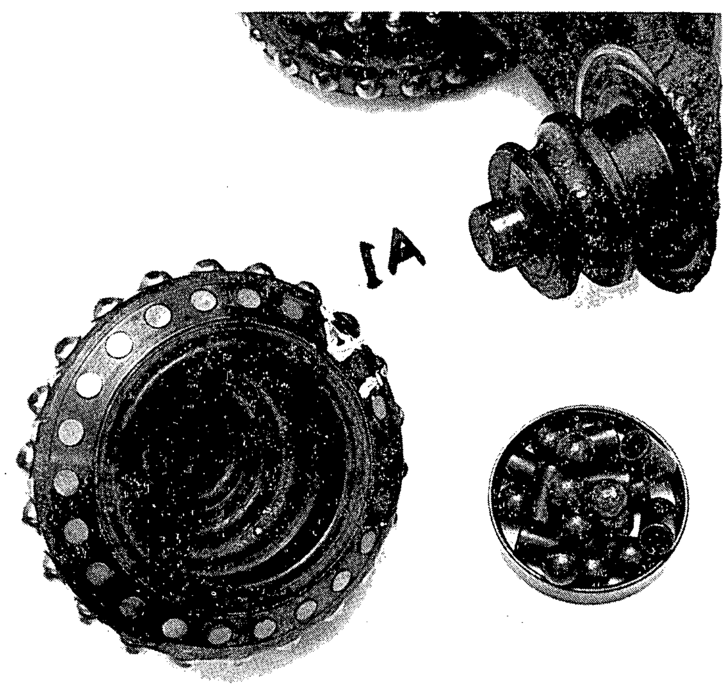

Figure 6. Cone, lug, balls and rollers of conventional bit "A", lug #1, showing wear on balls and ball races.

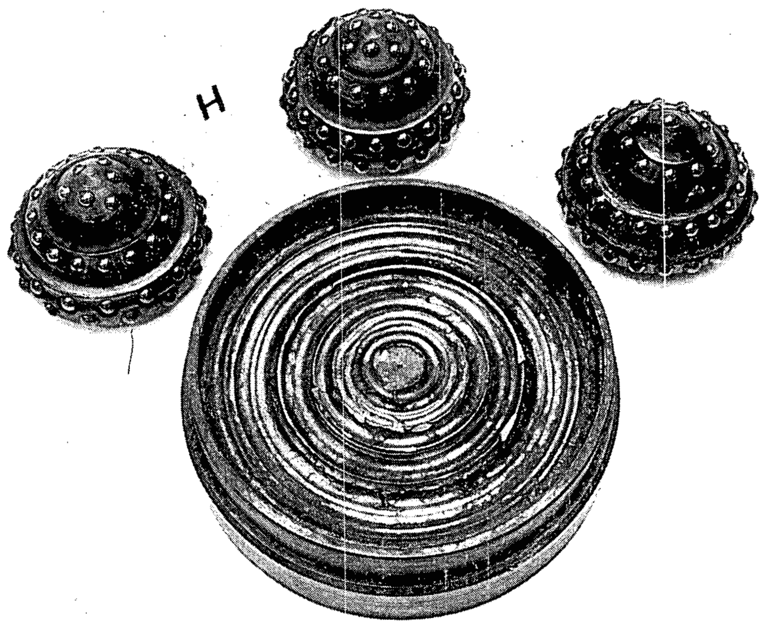

Figure 7. Pad and cones for experimental MK-II bit "H".

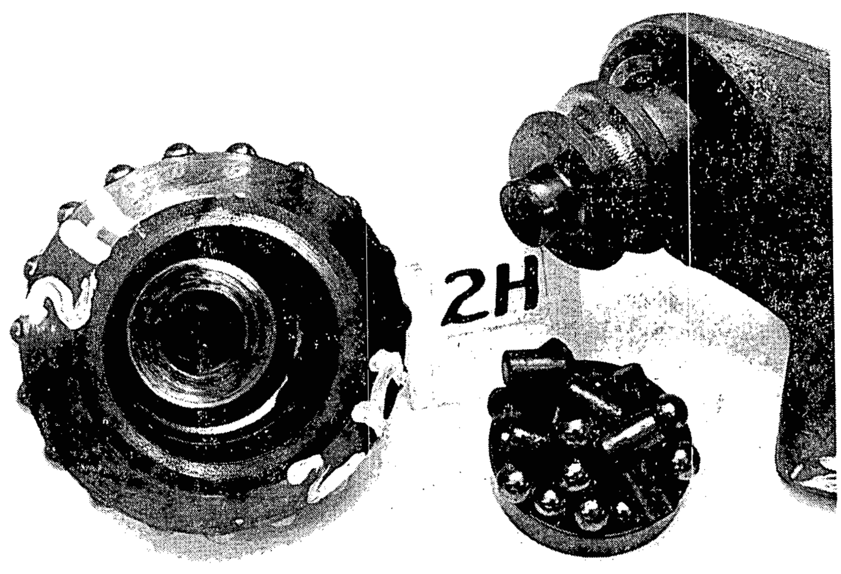

Figure 8. Cone, lug, balls and rollers from experimental MK-II bit "H", lug #2.

TABLE II

WEAR MEASUREMENTS FOR CONVENTIONAL AND MK-II EXPERIMENTAL BITS TESTED AT 316°C IN GEOTHERMAL WELLBORE SIMULATOR

	CONVENTIONAL BIT "A""	MK-II BIT "G"	MK-II BIT "H"
LOAD, POUNDS	20,000	25,000	20,000
RUN-TIME, MINUTES	150-180[3]	120	100
LUG WEAR[1]			
Friction Pin	0.012	0.002	0.000
Ball Race	0.030	0.016	0.040
Roller Race, IN[2]	0.044	0.004	0.007
Roller Race, OUT[2]	0.060	0.003	0.003
CONE WEAR[1]			
Friction Pin	0.001	0.001	0.000
Ball Race	0.018	0.000	0.004
Roller Race, IN[2]	0.025	0.006	0.007
Roller Race, OUT[2]	0.033	0.005	0.015

1. All wear measurements in inches; values shown are maximums.
2. Wear causes taper, two measurements are made; see Figure 9 for illustration of "IN" and "OUT" designations.
3. Bit "A" ran for five hours and 16 minutes, but cones locked between 150-180 minutes into test, at which time wear on bearing surfaces would have stopped.

The roller races on the cones and underside of the lugs on all three bits experienced tapered wear, hence two measurements, designed "IN" and "OUT" are listed in the table. Figure 9 illustrates where the measurements were taken, and also gives the nominal dimensions for the 6-3/4 inch Reed M83-JA bit.

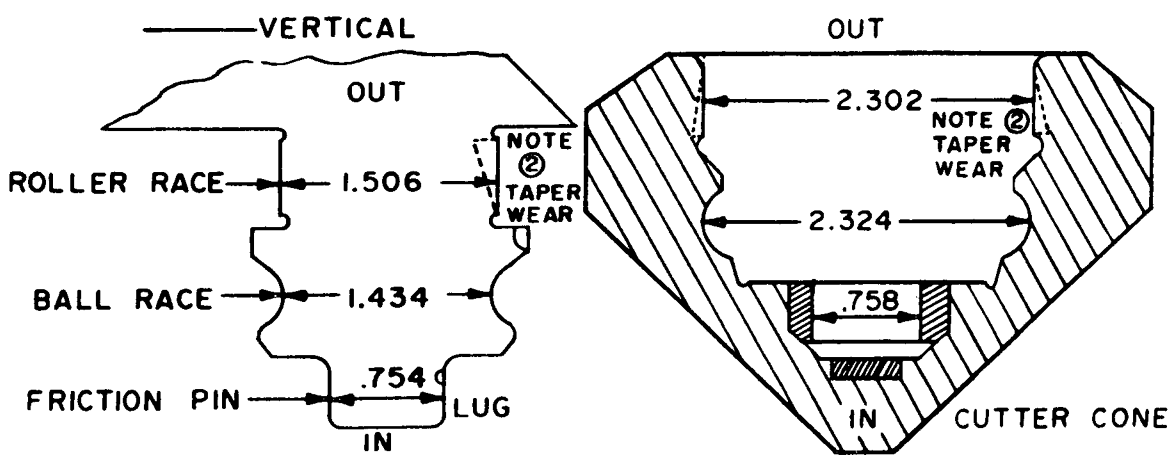

Figure 9. Locations for wear measurements of Table II (all dimensions are in inches).

The most significant differences in wear between the conventional bit and the experimental bits was found in the friction-pin and roller races of the lugs. The roller races of the cones also showed significant differences. Wear of the roller races is of particular concern, since it generally results in a change of the effective "journal angle" of the cones (Figure 10). All but one of the failed bits recovered from geothermal drilling operations during Phase I were found to have tapered wear which resulted in a decrease in the effective journal angle. The change in journal angle decreases the angle at which the gage inserts meet the hole wall, causing shearing of the rock to take place before sufficient compressive loading can be reached to cause crushing. Crushing is preferable, since

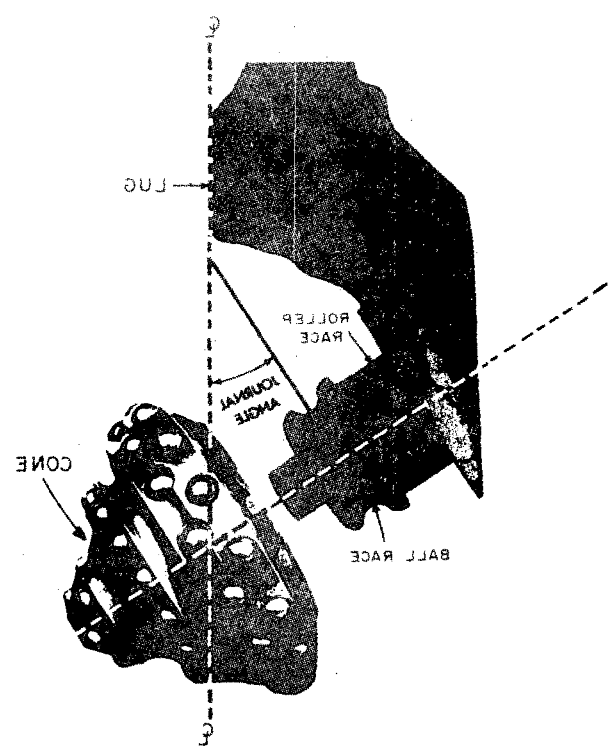

Figure 10. Definition of journal angle.

tungsten carbide is excellent in compression, but wears rapidly in scraping applications. Thus, the tapered wear of bit "A", and the greatly reduced amount of such wear in the two experimental bits, is probably the most significant finding of the tests.* The amount of wear on the races and friction pin of the cones of the experimental bits would probably have been less if the intended surface hardness of R_C 57-58, rather than R_C 47, had been attained. The breakage of the lug on experimental bit "G" indicates insufficient fracture toughness for the H-13 tool steel. The implication of these test results for selection of materials for the next generation of experimental bits will be discussed under "Materials Selction for MK-III Bits"

*It should be noted that the taper-wear experienced by the laboratory-tested bits results in an increase in journal angle rather than a decrease, as was the case for the field bits. This was probably due to the fact that the mild-steel pad did not support the out-thrust of the cones as well as the rock walls of an actual wellbore.

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

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

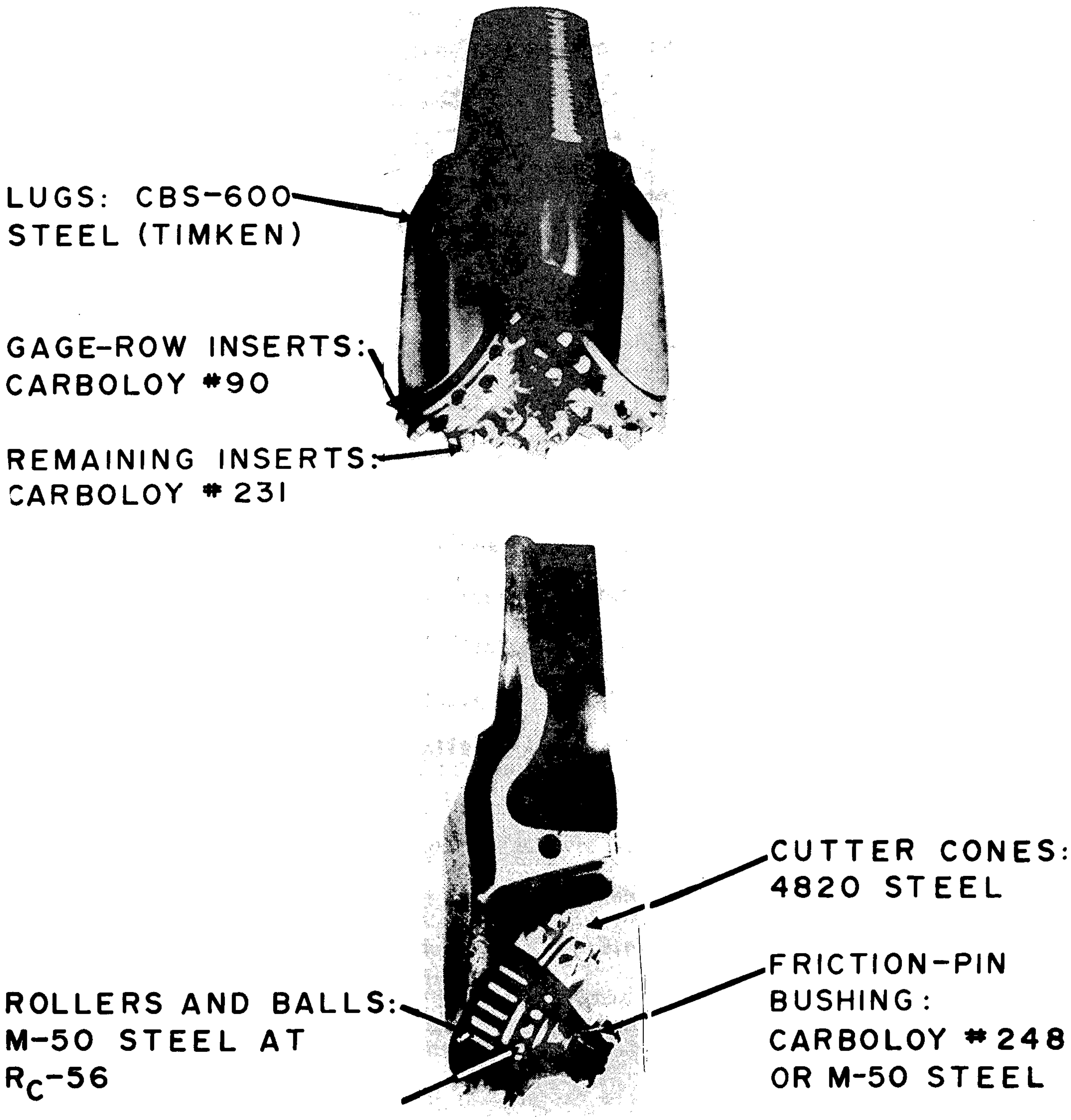

Figure 11. Materials selected for third generation of experimental unsealed bits.

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.*

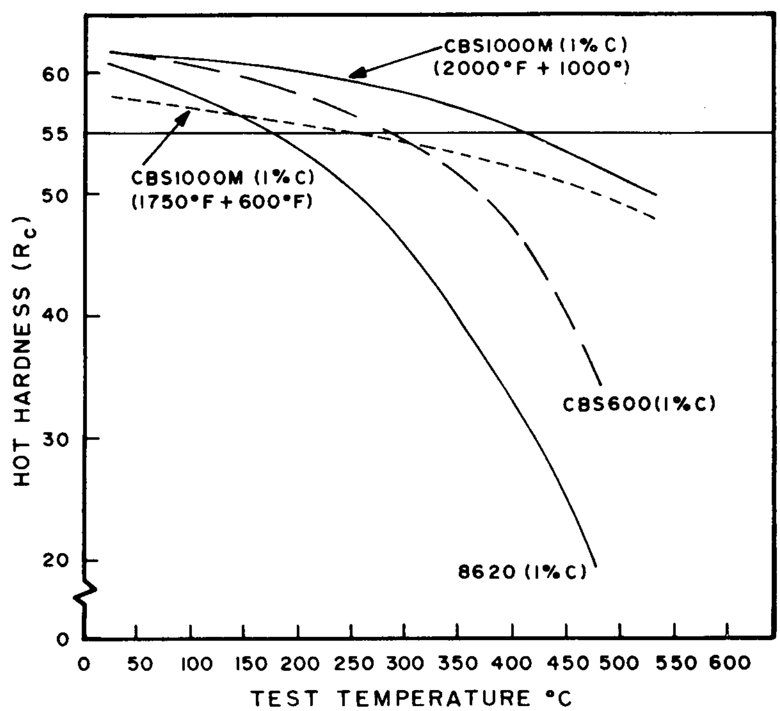

Figure 12. Hardness versus temperature for bit lug materials. (Timken Corporation)

*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 relationship between race hardness and bearing life* is given as:

$$\text{Bearing life} = 500\ H\left(\frac{33.3}{S}\right)\left[\frac{W_o}{W}\right]^{3.33} \quad \text{(hours)} \qquad (1)$$

where:

H = hardness factor (see Table III)

S = rotary speed (RPM)

W = bearing load

W_o = bearing load with produces life of 1 million revolutions (R_c = 58)

Using the values obtained from Figure 12 for 8620 and CBS-600 at 300°C, the hardness factor table* (Table III) indicates that the service life for

TABLE III

BEARING LIFE FACTOR (H) AS A FUNCTION OF ROCKWELL-C HARDNESS

R_c	H	R_c	H
58	1.00	42	0.012
56	0.88	40	0.0064
54.4	0.74	38	0.0036
54	0.69	36	0.0020
52	0.44	34	0.0011
50	0.21	32	0.0006
48	0.10	30	0.0004
46	0.05	28	0.0002
44	0.023	26	0.00014

*The formula and table appear in several ball and roller bearing catalogs and are based on the fatigue life of the races.

the CBS-600 should be about 15 times greater than that of 8620, at 300°C. This improvement could also be utilized to increase the weight used on the bit; if a bearing life improvement factor of three were sought, Equation 1 indicates that the weight-on-bit could be increased by a factor of 1.6. Thus a bit with CBS-600 lugs could theoretically be run at 178 KN (40,000 pounds) with three times longer life than a conventional bit run at 111 KN (25,000 pounds), at 300°C.

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

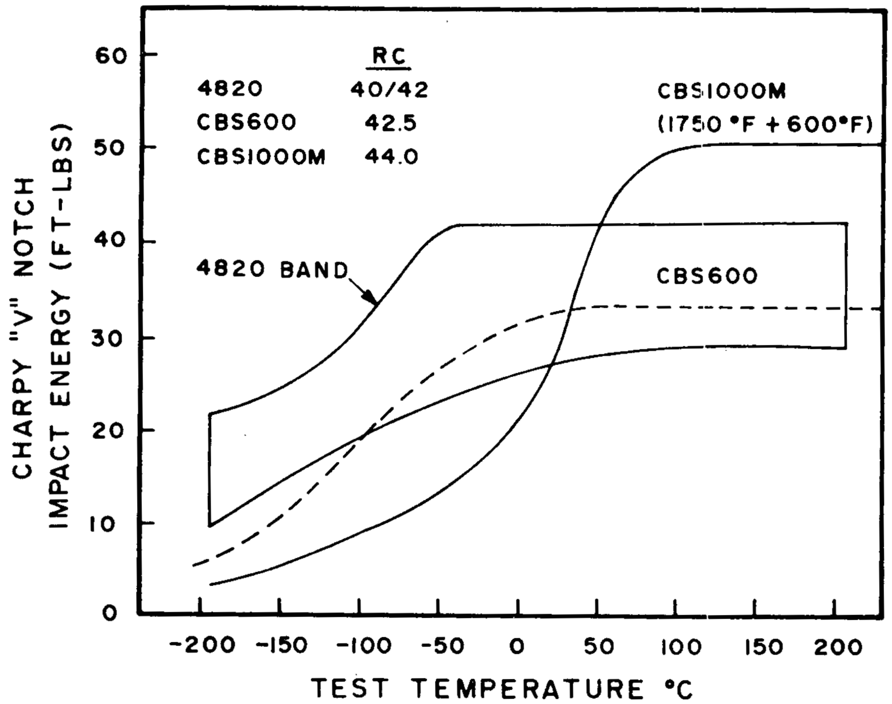

Figure 13. Charpy impact energies for uncarburized cores of CBS-600, 4820, and CBS-1000M as a function of temperature (Timken data).

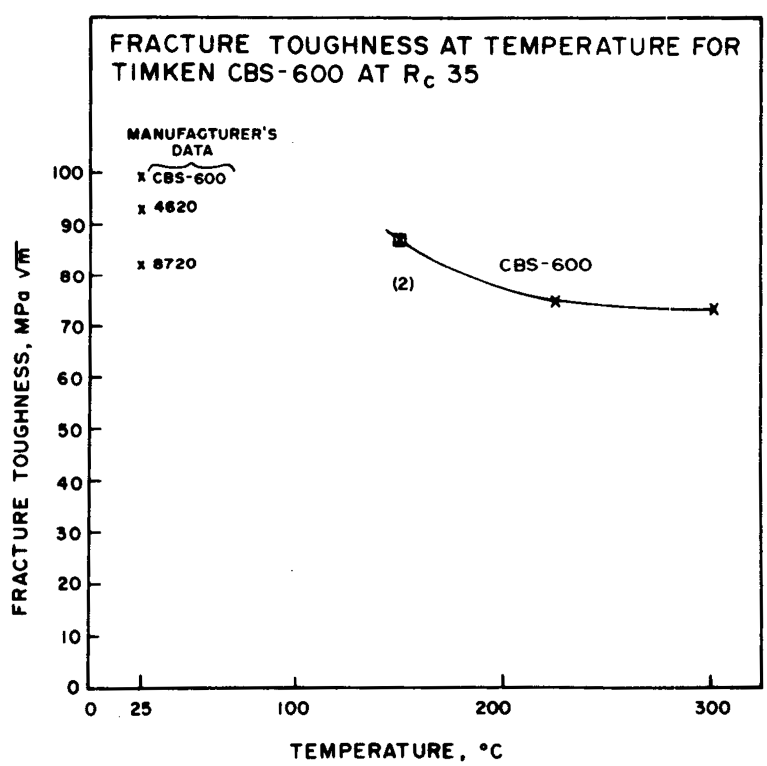

Figure 14. Fracture toughness of Timken CBS-600 (R_C 35) versus temperature as determined by laboratory tests (room temperature points for CBS-600, 4620, and 8720 are Timken data).

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.

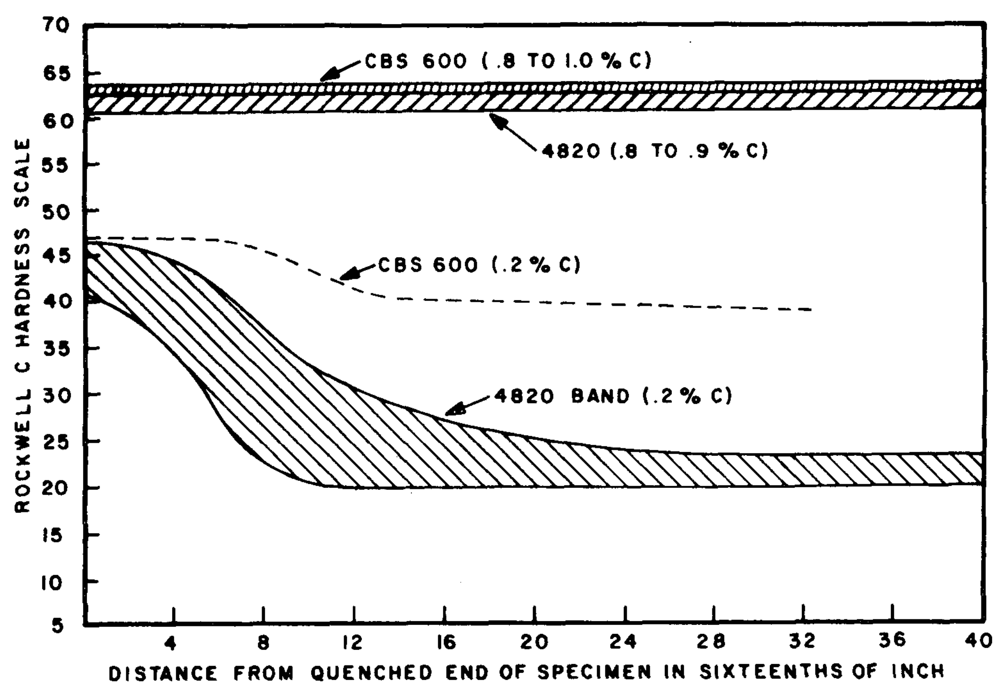

Figure 15. End-quench hardenability for 4820 and CBS-600 (Timken data).

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.

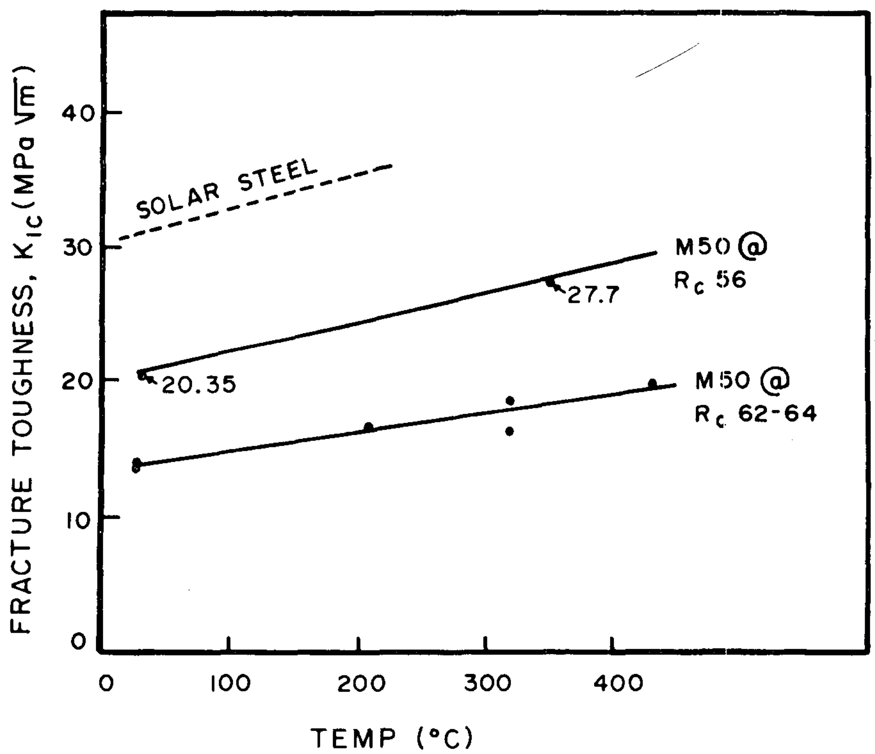

Figure 16. Fracture toughness for the roller bearing steels.

*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.

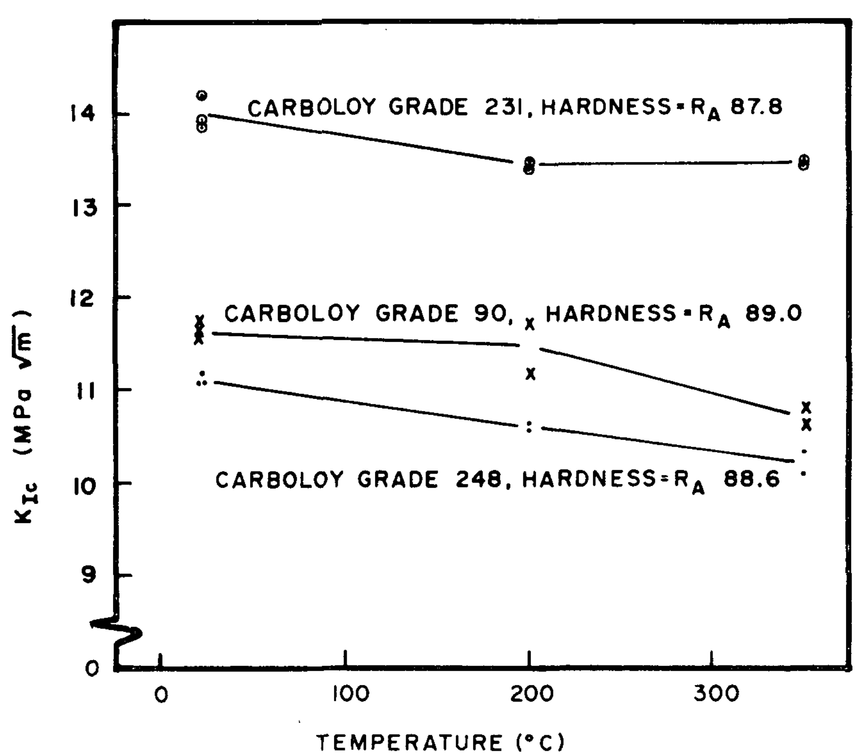

Figure 17. Fracture toughness for tungsten-carbide components.

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.

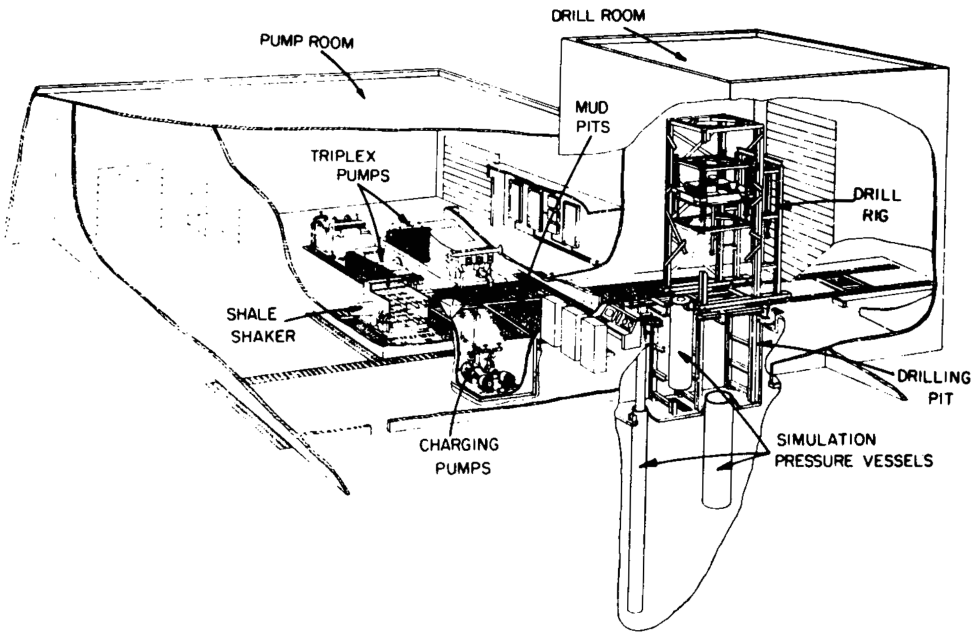


Figure 18. The Drilling Research Laboratory.

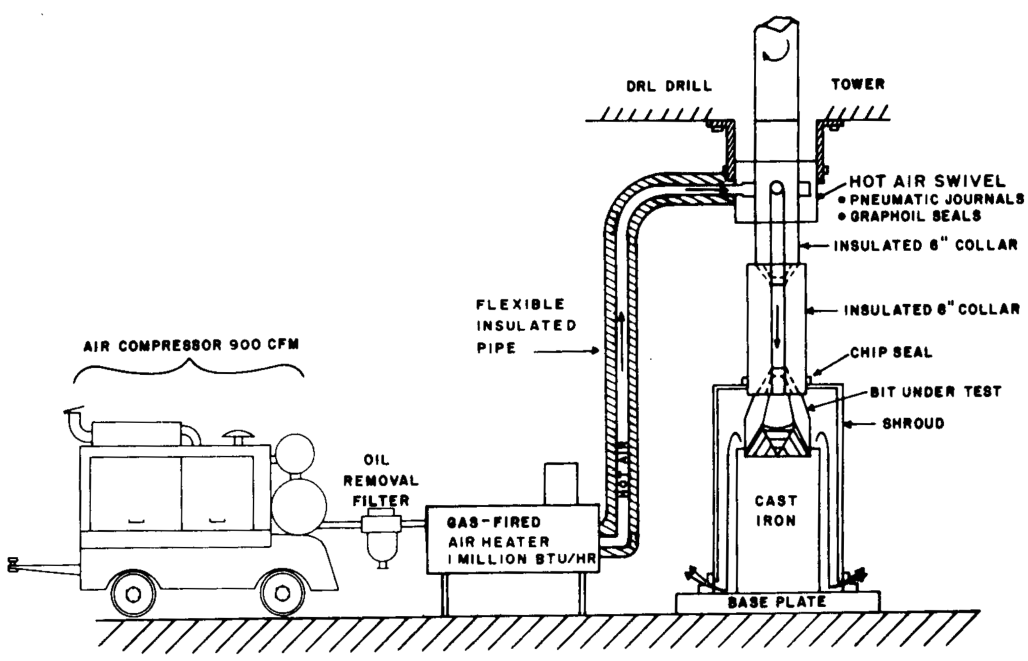


Figure 19. Geothermal Air Drilling Test Facility.

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

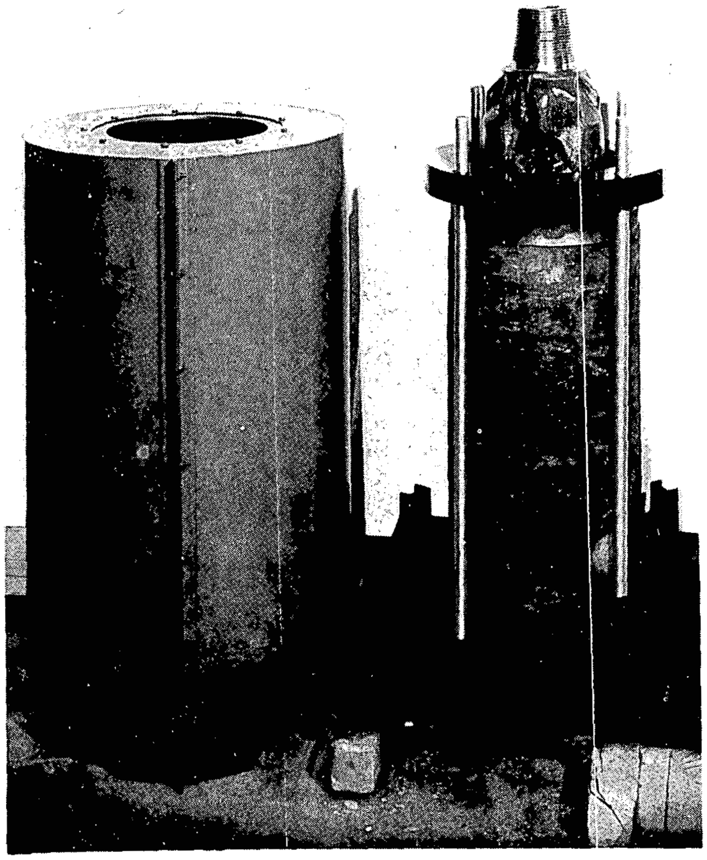


Figure 20. Shroud, base plate, pad and drill bit.

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.

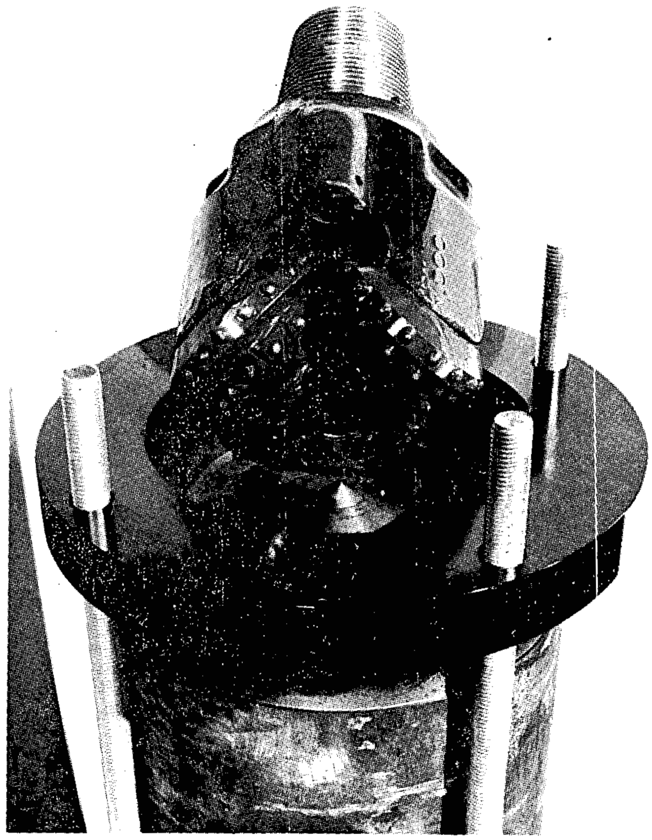


Figure 21. Cast-iron billet showing premachined contour.

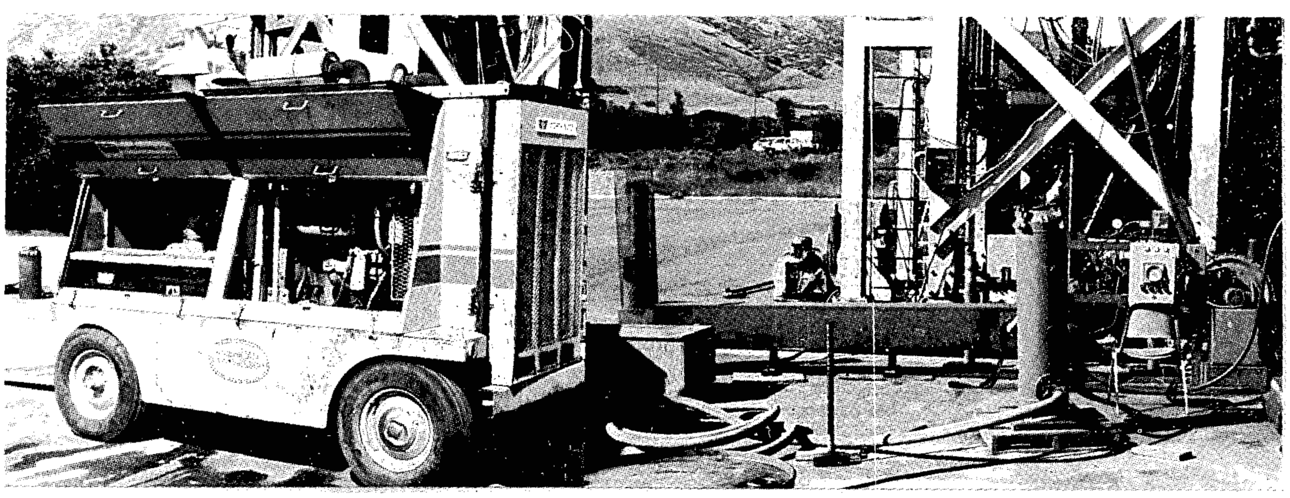


Figure 22. Geothermal air drilling system showing test assembly, drill rig and air equipment.

The Seal Test Facility

This subject is covered extensively in Reference 13, including design rationale, capabilities, testing procedures, and detailed descriptions of the hardware and instrumentation. The basic capabilities of the tester (Figure 23) are listed in Table VII.

The anticipated mechanical eccentricities encountered in drilling are simulated in the tester (referred to as "stroke" and "wobble" in the data); these can be highly significant to seal life, especially when abrasives are present. The pressure on both the lubricant side, and the "wellbore" side

Figure 23. Seal Test Facility.

TABLE VII

SEAL TESTER CAPABILITIES

Parameter	Range	Type of Adjustment
Temperature	20°C - 425°C	External
RPM	50 - 2,000	External
Pressure	0 - 21 MPa (3,000 psi)	External
Well Fluid	Water, Steam, Mud	Prior to Test
Radial Motion	$\pm$0.025 mm - $\pm$0.043 mm ($\pm$.001 - $\pm$.017 inch)	Prior to Test
Axial Motion	0.08 mm - 1.27 mm (.003 - .050 inch)	Change cam
Abrasives	any	Prior to Test

of the seal can be controlled and monitored; differentials as low as 0.07 MPa (10 psi) can be observed in the presence of a common 21 MPa (3,000 psi) pressure. Seal failure is detected by continuous monitoring of the fluctuations in the differential pressure which are caused by the axial stroke of the drive shaft (Figure 24).

Seal Test Results

The results of the first 115 seal tests were reported in Reference 13. These tests indicated that Viton and Buna-N were the best available high-temperature elastomeric seal materials, having a temperature limit of about 235°C and 225°C, respectively, in the standard four-hour screening test.

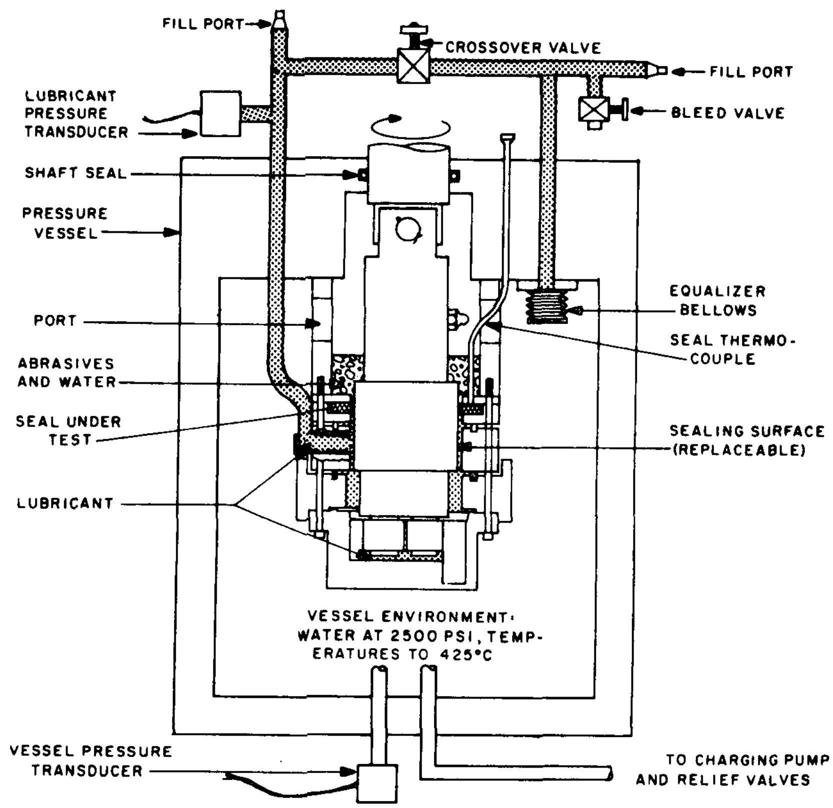


Figure 24. Differential pressure system for seal failure detection.

Most of the 37 tests run in the present reporting period were life tests, which tend to be longer than the four-hour screening test. The significant findings from these tests are as follows:

(1) The lubricants used were found to have a large effect on seal life; the standard drill bit grease, used in most of the first 120 seal tests, was particularly detrimental to seal life at these temperatures.

(2) Viton, including peroxide-cured Viton, provided a service life on the order of 100 hours at 200°C when a bentonite-base mineral oil lubricant was used.

(3) Buna-N, the conventional elastomer, provided a service life of 18-1/2 hours with the bentonite-base mineral oil lubricant; a service life of 100 hours should be attainable at 175°C.

A protective coating of a teflon-like material, Parylene-C, was applied to several types of seals; this technique had proved beneficial[17] elsewhere for protecting static seals in geothermal applications. The Parylene-C can protect the elastomer from chemical attack, allowing the use of an elastomer which may have superior tensile strength at temperature, but poor chemical resistance. In all of the six tests run, the relatively thin (0.04 mm or 0.0015 inch) coating wore through at the seal interface; bonding of the coating to the elastomer was marginal. Thicker coatings and improved bonding techniques are currently being studied. The test data follow, with a discussion of the performance of each type of seal.

Fluoronated Polyphosphazene Rubber

This elastomer (Firestone PNF-200) is an inorganic-backbone polymer based on a phosphorous-nitrogen group. The results of one test (#12) appeared in Reference 13. Table VIII gives the results of three new tests, including two Parylene-C coated seals.

All of the PNF-200 seals experienced severe molecular degradation, as evidenced by the durometer shifts, and general appearance, especially on the sealing surfaces. Figures 25, 26, and 27 illustrate the final condition of the seals tested.

Fluorosilicone Rubber

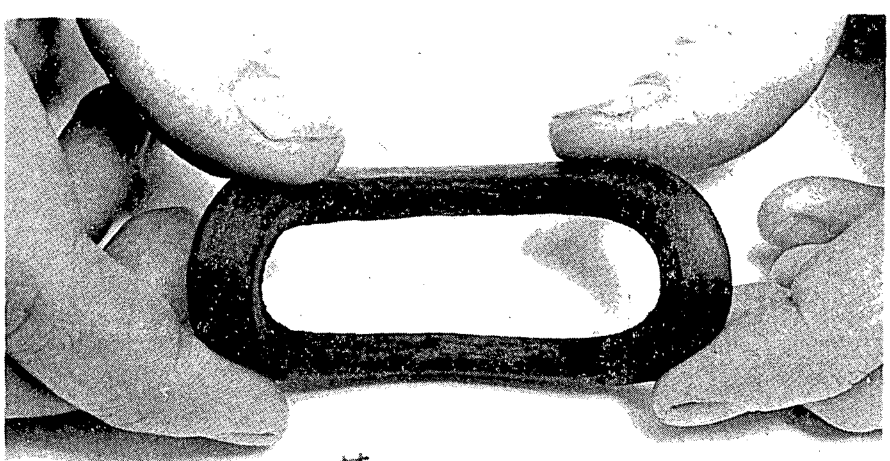
Dow-Corning supplied an experimental fluorosilicone compound designated "TR-70"; seals were molded in the standard oval configuration, and two were

TABLE VIII

TEST DATA FOR FLUORONATED POLYPHOSPHAZENE ELASTOMERIC SEAL

Test #	Temp °C	Installed Compression, % (Note 1)	Stroke mm and (inches)	Wobble mm and (inches)	RPM	Lube	Abrasives yes/no (Note 3)	Durometer, Shore A Before/After (Note 4)	Seal Life Hours	Comments
12	200	6.4	0.25 mm (0.010 ")	±0.18 mm (±0.007")	90	RRB[2]	no	63,59/50,39	4:00[5]	95% of grease-seal I.D. ruined since this test was run with a cold start - it will be repeated later with a warm start.
143	200	5.5	"	±0.13 mm (±0.005")	"	V-70[6]	yes	66,64/50,40	8:37	Seal failure was gradual. I.D. showed definite deterioration.
147	200	8.7	"	"	"	LHT[7]	yes	87,80/30,10	15:45	Parylene coating, 0.04 mm thick. Coating disintegrated, elastomer totally degraded.
148	200	6.7	"	"	"	"	no	85,35/60,30	14:45	Parylene coating stayed on seal except on I.D. Elastomer heavily degraded on I.D.

1. Percent compression = $\frac{\text{seal thickness - gland depth}}{\text{seal thickness}}$ X 100%, where "seal thickness" is one half of the difference between outer and inner diameter of the entire seal.
2. Conventional Reed rollerbit grease.
3. Abrasives are a mixture of repulverized Geyser's Graywacke sandstone and common feldspar sand.
4. Durometer values are given for initial reading, and after 30 seconds.
5. Fixed-interval test.
6. Valvoline 70-weight motor oil.
7. Lubriplate "Hi-Temp" bentonite-base mineral-oil by Fiske Refinery.



#143

Figure 25. PNF-200 seal, 8 hours, 37 minutes at 200°C using 70-weight motor oil.

Figure 26. PNF-200 with Parylene-C coating (foreground); 15 hours, 45 minutes, at 200°C using Bentonite-base grease.

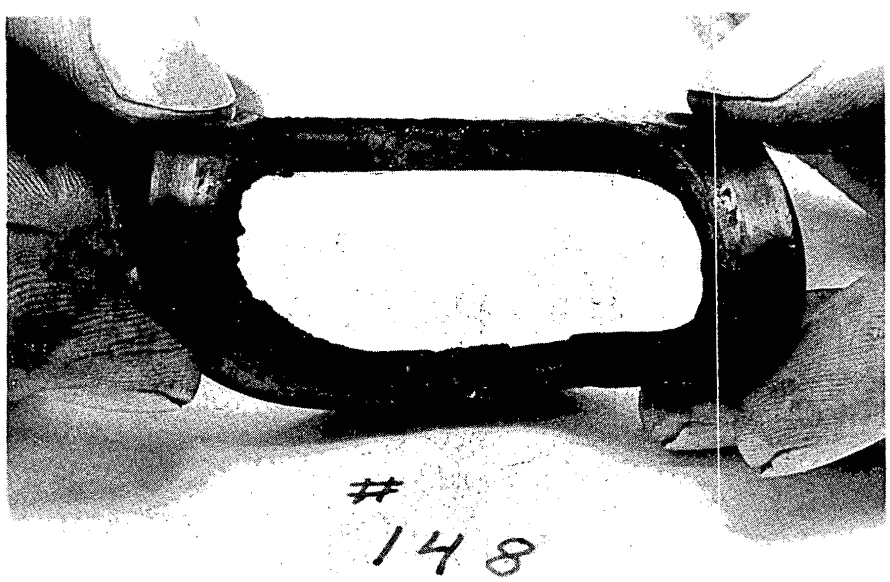


Figure 27. PNF-200 with Parylene-C coating; 14 hours, 37 minutes, at 200°C without abrasives, using Bentonite-base grease.

tested (tests #136 and #137). In addition one of the Parker fluorosilicone seals* was coated with Parylene-C and evaluated (test #142). The results of these tests are reported in Table IX.

TABLE IX

TEST DATA FOR FLUOROSILICONE RUBBER

Test #	Temp °C	Installed Compression, %	Stroke mm and (inches)	Wobble mm and (inches)	RPM	Lube	Abrasives yes/no	Durometer, Shore A Before/After	Seal Life Hours	Comments
136	200	8.7	0.18 mm (0.010")	±0.13 mm (±0.005")	90	V-70[1]	yes	76,75/73,71	6:35	Dow-Corning material. Seal failed due to wear at the sealing surface. Note good durometer retention
137	200	8.3	"	"	"	"	yes	" " — —	—	Dow-Corning Material. Test invalid due to equipment malfunction
5	200	7.8	1.02 mm (0.040")	±0.10 mm (±0.004")	200	L.H.T.	no	73,67/57,53	4:00	Parker Material, fixed duration test. 15% grease loss.
142	200	7.8	0.18 mm (0.010")	±0.13 mm (±0.005")	90	L.H.T.	yes	— —	2:00	Parker material with Parylene-C coating. Coating wore through at seal I.D., sealing surface wore out.

1. V-70: Valvoline 70 wt. motor oil; L.H.T.: Lubriplate "Hi-Temp" bentonite grease.

The results of test #5 are presented again for comparison with test #142; the presence of abrasives is probably responsible for the shortened life in test #142. The Parylene-C coating was not of much benefit. The comparatively favorable results of the "TR-70" in test #136, namely the six-hour life and small durometer shift, suggest that more tests should be run using the Lubriplate "Hi-Temp" lubricant, or promising candidate lubricants, as defined with the lubricant tester (to be discussed).

*Results of four tests on this proprietary material were reported in Reference 13.

Wire-Mesh Reinforced Buna-N

The results of three previous tests on wire-mesh reinforced Buna-N seals were reported in Reference 13. These seals experienced severe mechanical problems, *i.e.*, large segments of elastomer separated from the stainless steel wire mesh. Since these seals were slightly out of tolerance due to molding problems caused by the wire, they experienced more compression than was desired. Seal test #138 (Table X) utilized a specially modified seal carrier to provide about seven percent compression. The test lasted only 20 minutes, with pitting of the elastomer at the sealing surface, similar to that observed in previous tests.

TABLE X

TEST DATA FOR WIRE-MESH BUNA-N, SEALOL METAL BELLOWS, KALREZ COMPOUND #1050

Test #	Temp °C	Installed Compression, %	Stroke mm and (inches)	Wobble mm and (inches)	RPM	Lube	Abrasives Yes/no	Durometer, Shore A Before/After	Seal Life Hours	Comments
138	200	6.9	0.25 mm (0.010 ")	±0.13 mm (±0.005")	90	V-70	yes	– –	0:20	Wire-mesh reinforced Buna-N, using specially constructed seal carrier to provide 7% compression. Seal failed due to breakdown of elastomer on I.D.; chunks of material separated, exposing wire-mesh.
151	125	21.7	"	± 0.025 (±0.001")	200	Note 1	"	82,79/82,79	31:40	Kalrez #1050 in SAE #2-329 O-ring configuration. Seal failed due to compression-set of elastomer. Degradation and abrasive wear were minimal.
152	200	3.8 mm (0.150")	"	"	90	LHT	no	n/a	7:00	Metal bellows seal with carbon face-seal ring. This test was run to gain experience for handling metal bellows face-seals. Failure caused by fatigue in bellows (unit was "factory reject").

Sealol Metal Bellows

The sealol metal bellows fac-seal (Figure 28, Table X) was a sample of a standard product provided by the manufacturer. It was tested to gain insight into the problems and capabilities of both the face-seal and the metal bellows. Since the space available in the bit is very limited, a new, highly compact metal bellows face seal would have to be developed. This test was thus required to help determine the feasibility of such a seal. The seal provided exceptionally low leakage until the bellows ruptured; since the unit tested was a reject, judgment on the bellows is reserved. The overall concept appears feasible, and work is proceding with Sealol on the joint development of a scaled-down face seal.

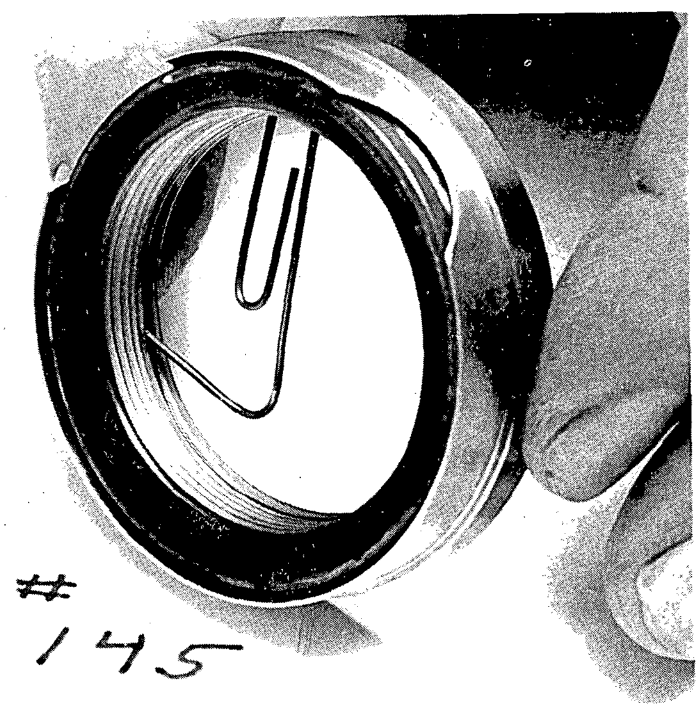


Figure 28. Metal bellows face seal.

Kalrez Compound #1050

The Kalrez compound #1050 was tested (Table X) in the #2-329 O-ring configuration, using an exceptionally high compression of 22 percent. This was done at DuPont's recommendation, to accommodate the "wobble" eccentricity, although this was reduced to ±0.025 mm. The seal life of nearly 32 hours indicates no major problems; the durometer was totally unaffected, and the general appearance was good (Figure 29).

Figure 29. Kalrez O-ring, showing compression set, after 32 hours at 125°C.

DuPont has submitted two new candidate Kalrez compounds, based on the results of test #152. The new seals are in the larger oval cross-section configuration to provide more radial compliance at lower stress levels. DuPont believes that while Kalrez cannot match Viton's mechanical properties at 200°C, it should be able to provide adequate tensile strength at 290°C.

Buna-N - The results of 46 tests on this elastomer, a proprietary compound formulated and molded by Parker Seal Company, were previously reported in Reference 13. The results of an additional 19 seal tests are presented in Table XI.

TABLE XI

TEST DATA FOR BUNA-N SEALS

Test #	Temp °C	Installed Compression, %	Stroke mm and (inches)	Wobble mm and (inches)	RPM	Lube	Abrasives yes/no	Durometer, Shore A, Before/After	Seal Life Hours	Comments
118-126	200	6.3	1.02 mm (0.040")	± 0.18 mm (±0.007")	90	Note 1	no	— —	—	Equipment checkout tests for refinement of seal failure detection.
127	"	6.6	0.25 mm (0.010")	±0.25 mm (±0.005")	90	V-70	yes	73,74/— —	14:15	Seal failed due to wear on I.D.
128	"	"	"	"	"	"	"	— — — —	16:20	Seal failed due to wear on I.D.
138	"	6.9	"	"	"	"	"	— — — —	0:40	Wire-mesh reinforced type. Seal I.D. experienced loss of large segments of material.
139	"	9.4	"	"	"	"	"	— — — —	0:20	Test never acted properly, cause unknown.
140	"	8.9	"	"	"	"	"	— — — —	14:40	Test terminated due to equipment malfunction.
141	"	7.8	"	"	"	"	"	— — — —	14:00	Exact time of failure uncertain due to equipment malfunction.
144	250	5.5	0.38 mm (0.015")	±0.18 mm (±0.007")	"	RRB	no	67,64/71,69	1:40	Seal tests started cold and run to 200°C, held at 200°C for 1 hour then increased to 250°C.
145	200	5.1	0.25 mm (0.010")	±0.15 mm (±0.006")	90	LHT	no	69,65/75,70	1:00	O-ring, SAE #2-329. Inadequate sealing, probably due to low compression, test halted.
146	200	15.9	"	±0.13 mm (±0.006")	"	"	"	69,65/80,70	13:50	O-ring, SAE #2-329. Seal was run at 200 °C for 1 hour w0 min. then lowered to 125°C to simulate soak/run. Seal failed due to compression set.
149	200	7.4	"	"	"	LHT	ues	— — — —	18:30	Oval seal with 0.04 mm parylene-C coating. Coating wore through at sealing surface. Test caused exceptional wear on shaft.

Note 1. Mobile - 1 synthetic oil, Dow-Corning #200 silicone oil, Valvoline 70-wt. non-detergent motor oil, and Lubriplate "Hi-Temp" grease were used for test #118-126. The motor oils tended to "crack" causing noxious odors.

Test #144 was run to check out part of the seal tester instrumentation, but it shows the detrimental effect of very high temperature. The seal was run at 200°C, using the conventional rollerbit grease, for one hour, at which time the test temperature was increased to 250°C, failure occurred in 25 minutes (Figure 30).

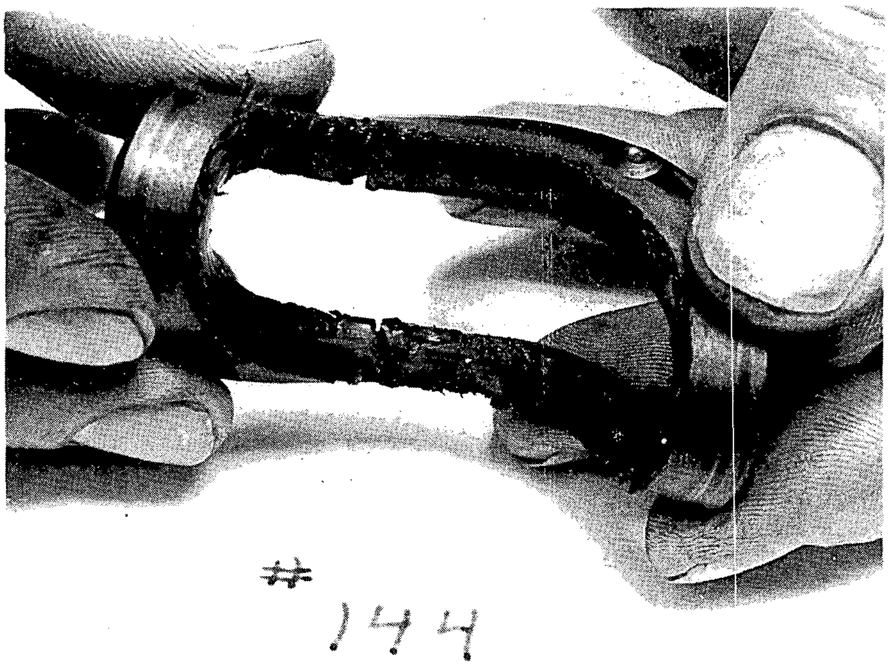


Figure 30. Buna-N seal run at 250°C without abrasives.

The seal shows signs of chemical degradation, as well as severe frictional wear (melt-flow), indicating rubber-to-metal contact due to insufficient lubrication by the rollerbit grease. Additional tests with a better lubricant might show some improvement in seal life, but probably nothing approaching a reasonable service life (50-100 hours) at this temperature.

Tests #127, #128, #140 and #141 indicate a life of about 14 to 16 hours at 200°C, with abrasives, using the 70-weight motor oil. The use of the bentonite-base grease (#149) increased the life to 18-1/2 hours. This seal had a thin coating of Parylene-C, which wore through at the sealing surface (Figure 31). The seal shows obvious signs of deterioration at the sealing

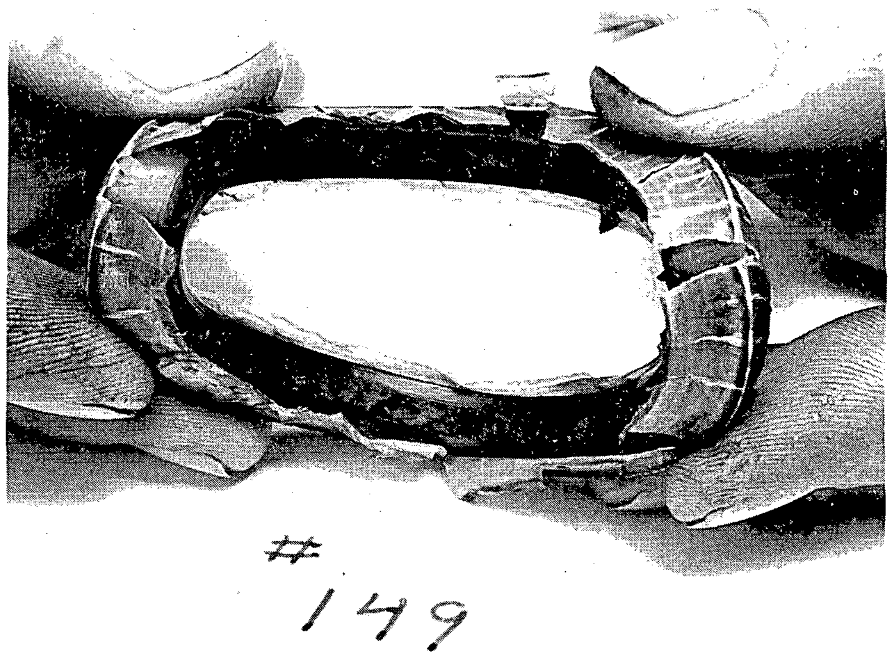


Figure 31. Buna-N oval with Parylene-C coating, run at 200°C with abrasives.

surface indicating chemical degradation of the elastomer. The replaceable shaft used for this test showed excessive wear, probably caused by the Parylene-C coating holding abrasives in contact with the shaft. Hence, the coating may actually have enhanced the abrasive damage to the elastomer. The use of a lubricant which can provide adequate lubrication of the seal interface, with minimal mechanical and chemical attack on the elastomer, may permit continuous service of Buna-N at or near 175°C; interaction with the lubricant testing program is needed at this point.

Peroxide Cured Viton - This elastomer was recommended by the DOE/DGE-sponsored program on elastomers for geothermal applications (GEM program), under the direction of Dr. Robert Reeber, as having superior resistance to chemical degradation, when compared to Viton.

The two seals run in 70-weight nondetergent motor oil (Table XII) proved inferior to standard Viton (Table XIII, tests #129-#133). The use of the

TABLE XII
TEST DATA FOR PEROXIDE CURED VITON

Test #	Temp °C	Installed Compression, %	Stroke mm and (inches)	Wobble mm and (inches)	RPM	Lube	Abrasives yes/no	Durometer Shore A Before/After	Seal Life Hours	Comments
134	200	8.7	0.25 mm (0.010")	±0.13 mm (±0.005")	90	V-70	yes	77,74/79,76	4:30	Seal failed due to wear on I.D.
135	"	7.3	"	"	"	"	"	77,74/79,75	4:30	Seal failed due to wear on I.D., wear pattern suggested elastomer was melting and flowing due to friction.
153	"	7.4	"	"	"	LHT	"	78,76/81,79	53:20	Seal failed due to degradation of elastomer, and wear.

TABLE XIII
TEST DATA FOR VITON SEALS

Test #	Temp °C	Installed Compression, %	Stroke mm and (inches)	Wobble mm and (inches)	RPM	Lube	Abrasives yes/no	Durometer Shore A Before/After	Seal Life Hours	Comments
129	200	6.3	0.25 mm (0.010")	± 0.13 mm (±0.005")	90	V-70	yes	— —	13:15	Seal failure due to wear*.
130	"	5.4	"	"	"	"	"	— --	4:45	Seal failed due to wear on I.D.
131	"	7.6	"				"	-- --	1:40	Seal accidentally subjected to 6.9 MPa (1000 psi) differential pressure, causing damage to seal and excessive leakage.
132	"	"	"	"	"	"	"	- -	9:05	Seal failure caused by wear
133	"	6.8	"	"	"	"	"	.	7:45	Seal failure caused by wear
150	125	19.4	"	"	90, 200	LHT	no	73. 70/80, 77	54:00	O-ring, SAE #2-329. Seal run alternately at 90 RPM, changing every eight hours. Failed due to wear on I.D. Degradation was minimal due to low test temperature.
154	200	7.4	"	"	90	"	yes	78, 76/82, 80	4:15	Defective seal, bubble developed and ruptured on sealing surface.
155	"	6.9	"	"		"	"	77, 74/82, 80	93:30	Seal began slow leak at 88 hours. Failure due to degradation and wear

bentonite-based mineral oil lubricant provided a very large increase in life (test #153) similar to the increase observed with Buna-N and Viton. Examination of the failed seal (Figure 32) revealed numerous small cracks

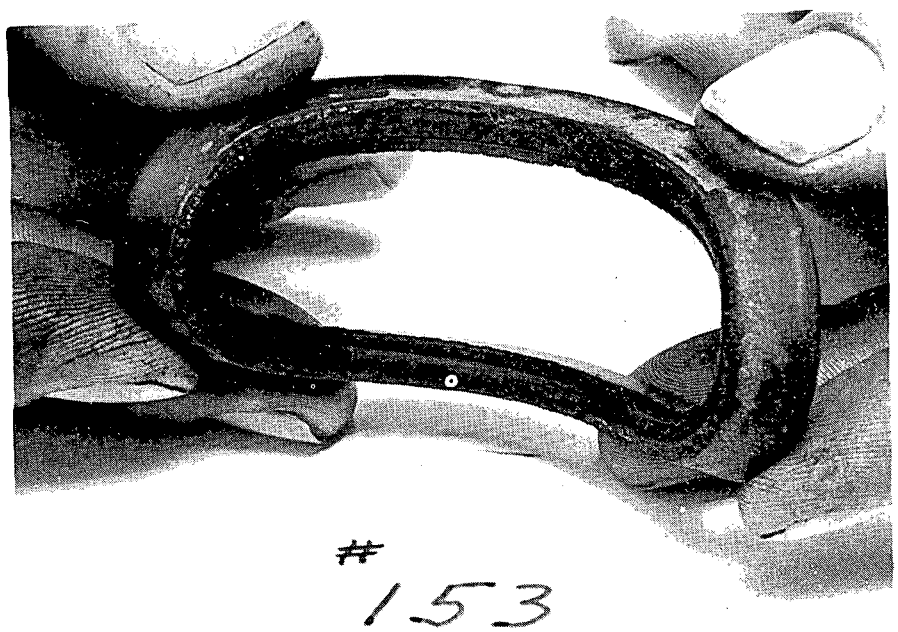


Figure 32. Peroxide-cured Viton run 53 hours in abrasives at 200°C.

indicating degradation of the elastomer; circular scarring suggests frictional wear caused by metal/elastomer contact; the durometer increased, indicating additional cross-linking (curing). The test data indicate roughly half as much life can be expected from this material, as compared to Parker #4205 Viton.

Viton - The Viton seals were molded by Parker Seal Company from their proprietary blend #4205. The previously reported tests had shown this elastomer to have only a slight (10°C) advantage over Buna-N in the four-hour screening tests. Tests run during this reporting period are detailed in Table XIII.

The tests run with 70-weight motor oil (#129, #130, #132 and #133) indicate seal lives which were less than those of Buna-N seals run in similar tests (Table XI, #127, #128, #140 and #141). One test run with the Bentonite-base grease (test #155) showed an exceptional seal life of 93 hours, 30 minutes, whereas a similar test (#149, Table XI) on Buna-N resulted in a life of only 18 hours, 30 minutes. The Viton seal (Figure 33)

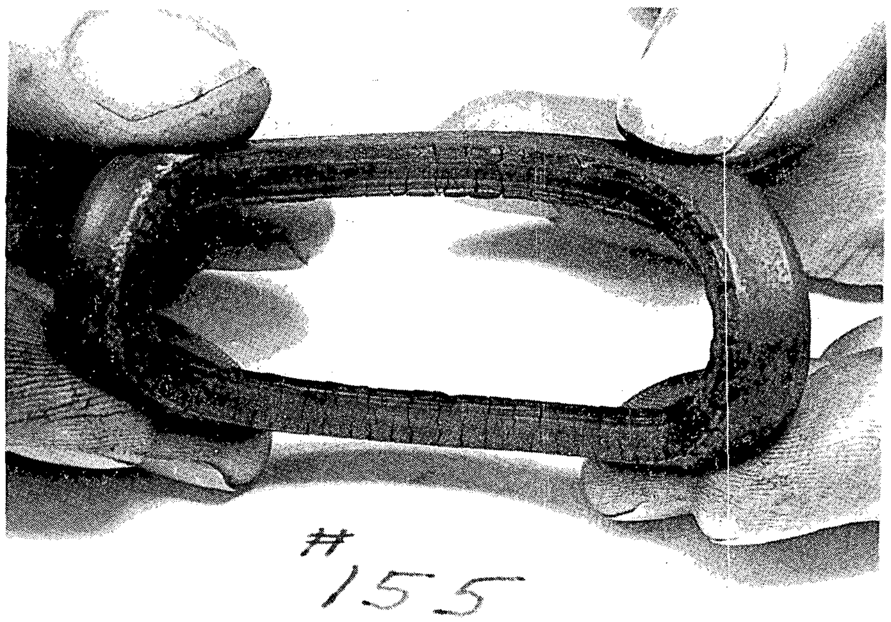


Figure 33. Viton seal run 93-1/2 hours with abrasives at 200°C.

appears to have failed due to degradation of the elastomer, as evidenced by the numerous vertical cracks, which provide leakage paths.

These observations indicate that useful service life at 200°C may be attainable with Viton, if a suitable lubricant can be found. Additional tests should be run under the same conditions as test #155.

LUBRICANT TEST PROGRAM

The conditions experienced by the lubricant in a sealed journal-bearing geothermal bit are unique. Lubricant manufacturers cannot predict performance, nor can any of the widely used lubricant testers (Timken, four-ball, Falex, LFW-1) be used to fully evaluate performance in a geothermal environment. The severe requirements for high load carrying ability at elevated temperatures are at least partially offset by the beneficial effects of an oxygen-free, pressurized* environment. The pressure raises the boiling point of liquid components of the grease, thus preventing their loss.

A lubricant test facility was constructed to evaluate candidate fluid-type lubricants, such as greases, oils and powders at temperatures to 427°C. The test utilizes a statically loaded wear block which contacts a rotating ring (Figure 34) in a pressurized nitrogen atmosphere. After 5,000 turns,

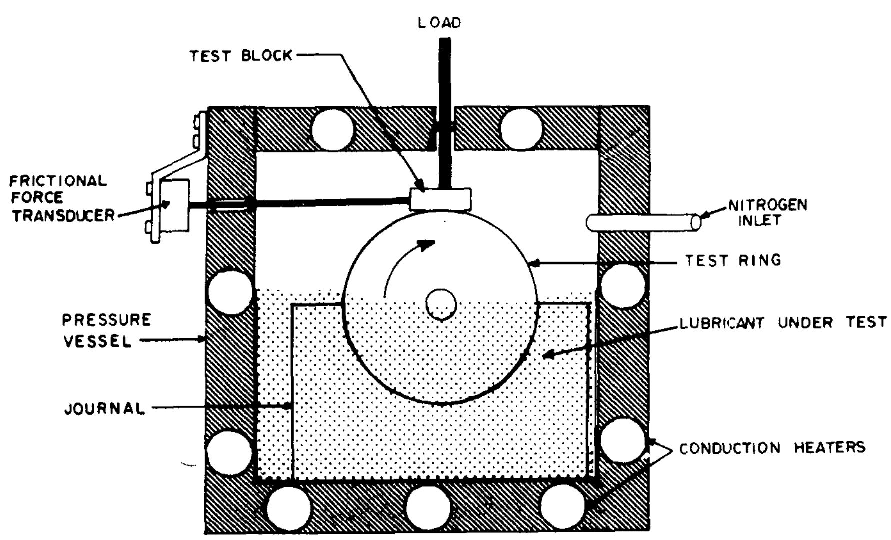


Figure 34. Lubricant tester schematic.

*In sealed drill bits, the lubricant pressure is equalized to wellbore pressure. Hydrostatic pressure is roughly 0.5 to 1.0 psi per foot of depth in fluid-drilled wells; drilling at the Geysers involves air pressures from 200 psi to 500 psi.

the wear block is removed and the width of the wear scar is measured. The test is run in accordance with ASTM specification D2714-68, written for the Alpha LFW-1.

The tester evaluates boundary-film lubrication as follows: The initial peak hertzian stress between the ring and block is selected to be higher than the load-bearing ability of the lubricant, thus inducing wear in the block which forms a journal, resulting in a more uniform distribution of the load. At some point in the test, the loading in the journal becomes sufficiently low to permit the lubricant to establish boundary lubrication; this event also produces a marked decrease in the frictional force, which is monitored on a strip-chart recorder. The duration of the test is sufficient for good lubricants to establish boundary lubrication. The load-bearing ability is determined by dividing the static load by the area of the wear scar; uniform stress is assumed. Operating parameters and machine capacities are detailed in Table XIV.

Figure 35 illustrates the test-ring assembly and the body of the pressure vessel. The test assembly rotates on two journal bearings which are lubricated by the lubricant under test; the test ring is located close to the left-hand journal. The complete lubricant test facility is shown in Figure 36.

Samples of 15 candidate high temperature lubricants were obtained from manufacturers, based on recommendations by manufacturers, consultants and bit industry personnel (Table XV). A screening program, detailed in Table XIV, was undertaken to isolate the more promising lubricants.

TABLE XIV

TEST CONDITIONS AND MACHINE CAPABILITIES FOR HIGH TEMPERATURE LUBRICANT TESTER

PARAMETER	ASTM D2714-68	SCREENING TESTS	MAXIMUM CAPABILITY
LOAD	667N (150 lbs.)	636N (143 lbs.)	2.7KN (600 lbs.)
MAXIMUM HERTZIAN STRESS[1]	467 MPa (67,700 psi)	456 MPa (66,100 psi)	933 MPa (135,000 psi)
TEMPERATURE	43°C (110°F)	316°C (600°F)	427°C (800°F)
PRESSURE (gage)	Not Applicable	0.79 MPa (115 psi)	1.38 MPa (200 psi)
RPM	72 ±1	Same	150 ±2
SURFACE VELOCITY	7.9 ±0.16 M/min (26 ±0.52 fpm)	Same	15.8 ±0.32 M/min (52 ±1.0 fpm)
RING TYPE[2]	S-25	Same	Any Material
DIAMETER	35 + 0.0025, -0.127 mm (1.3775 + .0001, -.0005 in)	Same	Same
WIDTH	8.15 ±0.127 mm (.321 ±0.005 in)	Same	Same
MATERIAL	SAE 4620 Steel	Same	Any
HARDNESS	R_c 58 - 63	Same	Any
FINISH	22 - 28 Microinch, RMS	Same	Any
BLOCK TYPE[2]	H30	H30	Any Material
WIDTH	6.35 + 0.013, -0.00 mm 0.250, + .0005, -0.00 in)	Same	Same
MATERIAL	SAE 01 Tool Steel	Same	Any
HARDNESS	R_c 27 - 33	Same	Any
FINISH	4 - 8 Microinch, RMS	Same	Any

NOTES:

1. Maximum Hertzian Stress Calculation, from References 18 and 19.
   $q_o = 5525\ P^{0.5}$ (psi)
   where P = load in pounds
2. Rings and Blocks purchased from FaVille-LeVally Corporation, Downers Grove, Illinois.

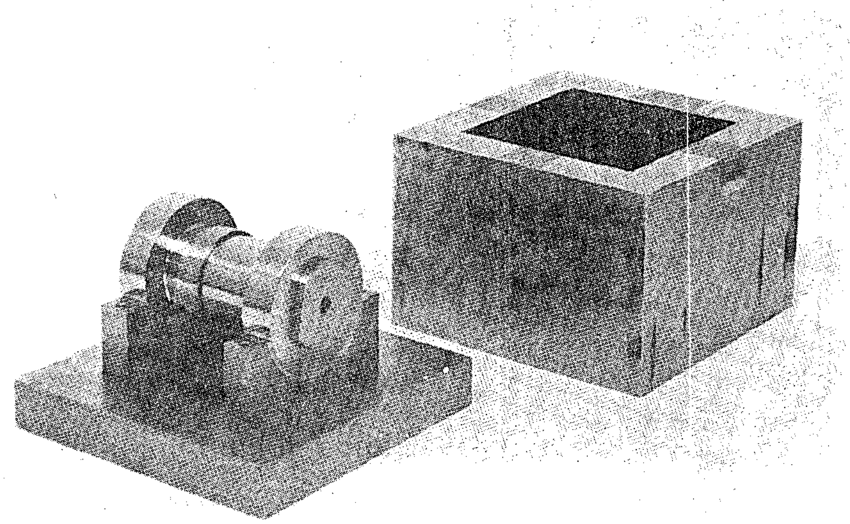


Figure 35. Test-ring assembly and partially completed pressure vessel.

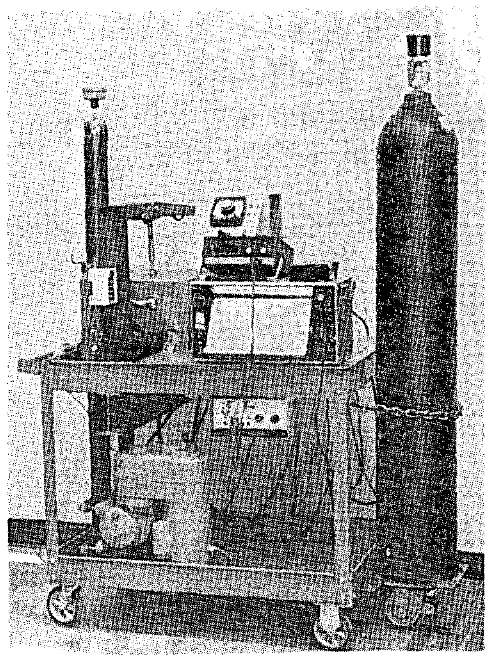


Figure 36. Lubricant test facility.

TABLE XV.

CANDIDATE GEOTHERMAL JOURNAL BEARING BIT LUBRICANTS

MANUFACTURER	PRODUCT
Atlantic-Richfield Co., Inc.	ARCO EP-Black Moly D
Dow-Corning, Inc.	#710-G Silicone Oil with Graphite
DuPont, Inc.	Krytox Fluorinated Grease
Eon, Inc.	D-20 Synthetic
Fiske Bros. Refining, Inc.	Lubriplate Hi-Temp
Fiske Bros. Refining, Inc.	604-D Hot Die Lubricant
Fiske Bros. Refining, Inc.	API Modified Thread Compound
Graphite Products Corp., Inc.	LS-11-1850 Anti-Seize
Graphite Products Corp., Inc.	LS-11-2100 Anti-Seize
Gulf Oil Corp., Inc.	419-C Grease (Silicone)
Mobil Oil Corp., Inc.	Mobil-1
Pacer Lubricants, Inc.	Pacer DH
Parr, Inc.	Plastilube
Wynn's Corporation, Inc.	High-Performance Lube Supplement
Wynn's Corporation, Inc.	Heavy-duty Concentrate

To date, tests have been completed on five of the 15 candidates; results are given in Table XVI.

TABLE XVI

HIGH-TEMPERATURE SCREENING TESTS

Test #	Lubricant & Manufacturer	Test Temp.	Wear Scar	Final Load Capability
4	Lubriplate Hi-Temp (Fiske)	315°C	2.17 mm	46.1 MPa (6.68 KSI)
5	Lubriplate Hi-Temp (Fiske)	426°C	2.59 mm	38.5 MPa (5.59 KSI)
6	LS-11-1850 Anti Seize (Graphite Products)	316°C	1.63 mm	61.7 MPa (8.93 KSI)
7	A.P.I. Modified Thread Compound (Fiske)	345°C	2.51 mm	39.7 MPa (5.76 KSI)
8	EON D-20 Synthetic Motor Oil (Eon)	312°C	7.39 mm	13.6 MPa (1.96 KSI)
9	Pacer DH Grease (Pacer)	313°C	0.85 mm	118 MPa (17.1 KSI)
10	Conventional Journal Grease	25°C	0.88 mm	113 MPa (16.4 KSI)
11	Conventional Journal Grease	315°C	1.54 mm	64.8 MPa (9.40 KSI)

A conventional journal-bearing bit grease* was run at ambient temperature (test #10); this test provides a basis of comparison for the candidate lubricants. Acceptable candidate lubricants should ideally be able to provide the same performance at elevated temperatures. The data indicate that the conventional bit grease is quite good at room temperature, with a load-carrying capacity of 113 MPa (16,400 psi). The Pacer DH** grease is the only product tested so far which has acceptable load-bearing ability at the elevated temperature: 118 MPa (17,000 psi). The results of the Pacer DH test is encouraging, and additional tests are planned to back up test #9.

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*Bit Manufacturer wishes to remain anonymous.

**The name has since been changed to Pacer "Syntemp #2 EP".

The lubricant tester could also be used to evaluate lubricant life and wear properties over longer periods of time at bearing loads anticipated in actual service. This would require the fabrication of conforming wear blocks having contact areas sized to simulate the desired loading stress. In this situation, boundary lubrication would be present at the start of the test, and any significant block wear would be indicative of breakdown of the lubricant. This type of test would require a great deal of operating time, since the life of a successful geothermal journal bit should be in excess of 100 hours.

CONCLUSIONS

Unsealed Drill Bits

Geothermal bits are required to drill hard, abrasive formations in hostile chemical environments at high temperatures. Air drilling, which may be necessitated by subhydrostatic geothermal reservoirs, results in even higher component temperatures. In these situations conventional unsealed rolling cutter "blast-hole" bits are used. Analysis of used bits revealed two areas where improved materials were required to increase bit life beyond the 10 to 20 hours frequently experienced:

(1) Bearings (including all elements of the roller, ball and friction bearings) require steels which maintain surface hardnesses above R_C 50 to at least 300°C, without compromising the high levels of fracture toughness required in rolling cutter bits (*e.g.*, at least 75 MPa$\sqrt{m}$ for the lugs).

(2) Gage-row tungsten carbide inserts require greater resistance to abrasive wear to prevent the excessive loss of gage diameter experienced in hard, abrasive formations. A tungsten carbide alloy with a hardness of at least R_A 89, and a minimum fracture toughness of 11 MPa$\sqrt{m}$ is required.

Prototype 8-3/4 inch unsealed geothermal bits were fabricated to facilitate evaluation of the selected steels, heat treating, and tungsten carbides. Materials choices were based on laboratory materials property tests and on laboratory full-scale high-temperature drilling tests on two previous generations of experimental geothermal bits. Overriding consideration was given to the adaptability of candidate materials to the manufacturers'*

*Hughes Tool Co., Reed Tool Co., Security Division of Dresser Industries, and Smith Tool Co.

forging, machining and heat treating equipment because the geothermal bit market cannot justify large tooling expenditures. Timken CBS-600 was selected for the lugs because of its excellent retention of hardness and fracture toughness to 300°C; M50 tool steel was chosen for the rollers and balls for similar reasons. General Electric/Carboloy grade #90 was selected for the gage-row inserts because of its high hardness (abrasion resistance) and good fracture toughness. A total of eight full-scale prototype unsealed geothermal bits were fabricated from the new materials. Two will be evaluated in the drilling laboratory under simulated geothermal air-drilling conditions. Six will be field tested at a geothermal site in back-to-back drilling with conventional bits; an improvement in bit life on the order of two to four times is expected.

Further improvement in bearing life is possible with Timken CBS-1000M and Teledyne-Vasco X2 "modified" steels. These alloys can provide adequate fracture toughness and bearing race hardnesses above R_c 50 to about 400°C, but will require higher temperature heat treating facilities than are presently available at bit manufacturers' production facilities.

Sealed Bits

Sealed journal-type bits provide penetration rates and overall life which generally result in a much lower cost per foot than is attainable with unsealed bits. However, existing sealed bits are inadequate for use in geothermal environments due to the:

(1) Short seal life at elevated temperatures, and

(2) Lubricant breakdown at elevated temperatures.

Two unique test facilities were constructed to evaluate the best high-temperature seals and lubricants currently available, and to encourage both seal and lubricant manufacturers to develop new products suitable for geothermal bits.

Elastomeric Seals - Tests conducted in the Geothermal Seal Test Facility indicate that fluorocarbon (Viton, Fluorel) elastomeric drill bit seals provide a 100-hour service life at 200°C (assuming the lubricant is compatible, see *Lubricants*). Buna-N seals will last 100 hours at 175°C. Both elastomers can withstand higher soaking temperatures (250°C and 225°C, respectively) for as long as four hours without seriously compromising performance. Fluorocarbon sealed bits can therefore be used for water, mud, or foam drilling into 250°C formations; circulation would be utilized to lower the bottomhole temperature below 200°C prior to drilling.

Elastomeric materials cannot be used to seal bits used in air drilling situations (geothermal or otherwise) due to the excessive component temperatures caused by friction in the bearings.

Hetrogeneous Seals - One test run on a metal bellows face seal (see Table X) indicated that long life and low leakage were possible with a nonelastomeric system. A detailed analysis of the technical problems associated with a mechanical sealing system revealed the following key considerations:

(1) Space is severely limited if the strength of the lugs and cones are to be preserved.

(2) High sealing forces and lapped sealing surfaces are required to minimize leakage.

(3) The sealing surfaces must be hard enough to withstand abrasive attack and have a low running friction to avoid thermal self destruction.

More development is needed to define mechanical seal systems which are compact enough to fit in within the cone without interfering with the load bearing regions of the bit.

Lubricants - Seal tests reported previously (see Reference 13) on fluorocarbon and Buna-N elastomeric seals, using a conventional rollerbit grease indicated a temperature limit of about 125°C. The much higher operating capabilities observed when these elastomers were run with the Lubriplate "Hi-Temp" lubricant (see Tables XI and XIII) clearly indicates that the maximum operating temperature for conventional sealed bits could be improved by 50 - 75°C solely through the substitution of an improved high-temperature lubricant.

Screening tests performed in the high-temperature lubricant tester indicate that Pacer DH grease is suitable as a journal-bearing bit lubricant at temperatures to 300°C. Further screening tests are planned to locate additional high temperature bit lubricants. Promising candidate lubricants are to be run in the Geothermal Seal Test Facility to determine their compatibility with fluorocarbon and Buna-N elastomers, and the mechanical seal designs.

ACKNOWLEDGMENTS

The authors first wish to express their deep appreciation to Reed Tool Company for its participation in the program. Reed has fabricated a total of 16 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, Terry Mayo, John Childres, Bill Schumacher, John Deane, Harry Mauzy and Larry Ledger assisted in planning, definition of processing procedures, and bit fabrication.

Don Ash, Bob Rardin, Kelsey Lumen, and Larry Hampshire of Union Oil Company's Geothermal Operations gave freely of their time for consultations on geothermal drilling procedures and problems.

Bill Maurer, Larry Remont, Bill McDonald and Jeddy Nixon of Maurer Engineering contributed to the development of heterogeneous seals, and the selection of candidate lubricants. John Day of Mudtech Divison of Maurer Engineering consulted on the nature and chemistry of drilling muds.

Bill Leslie of the Materials and Metallurgical Engineering Department of the University of Michigan conducted the search for high-temperature steels, and assisted greatly in the final selections of materials and heat-treating procedures for the MK-III bits. Bill also provided a thorough investigation of the state-of-the-art in high-temperature, corrosion-resistant alloys for use in springs for heterogeneous seals. Alexander Troiano of Case Western Reserve University provided assistance to Bill Leslie on the stress-corrosion cracking aspect of steels selection.

Bob Reeber, Department of Energy/Division of Geothermal Energy, Washington, D.C., encouraged participation in his program on Geothermal Elastomer Materials (GEM), thereby deepening our understanding of the the physical and chemical capabilities and limitations of elastomeric materials. Charles Arnold of Sandia Laboratories, and numerous other members of the GEM team have given freely of their time.

Additional thanks goes to those who, through informal conversations, increased our understanding of drill bit materials problems: Walter Littmann, Morgan Crow, W. S. Keller, Jim Langford, Jack Wood, Bob Williamson, Jim Young, Don Vanderford, Bob Clamon, Mike Conn, J. D. Morris, Rod Wilson, and Lee Goodman of Dresser Industries and Tom Oldham, Lloyd Garner, Stacy Oldham, and Irwin Oelke of Smith Tool Company.

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APPENDIX A

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.

Mr. P. W. Schumacher, Jr.
August 18, 1977
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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 hou.· wear-in procedure, should allow long duration geothermal wellbore 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.

Mr. Jon H. Barnette
September 20, 1977
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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

cc: C. Carwile, ERDA
M. M. Newsom, Sandia
W. C. Leslie, University of Michigan
Dewey Thiessen, Reed Tool
P. W. Schumacher, Reed Tool
Terry Mayo, Reed Tool
Harry Mauzy, Reed Tool
S. J. Green, Terra Tek
A. H. Jones, Terra Tek
L. M. Barker, Terra Tek
B. J. Sakashita, Terra Tek
R. W. Winzenried, Terra Tek

APPENDIX B

TerraTek

September 7, 1977

Mr. Clifton Carwile
Project Manager
Exploration Technology Branch
Energy Research and Development
Administration
20 Massachusetts Ave., N.W.
Washington, D.C. 20545

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

Mr. Clifton Carwile
September 7, 1977
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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
Project Engineer
Terra Tek, Inc.

Prof. William C. Leslie
Consultant to Terra Tek
University of Michigan

RRH-WCL/jlg

cc: J. Barnette,Sandia Laboratories
M. M. Newsom, Sandia Laboratories
W. C. Maurer, Maurer Engineering, Houston
L. Reamont, Maurer Engineering, Houston
S. J. Green, Terra Tek
A. H. Jones, Terra Tek
L. M. Barker, Terra Tek
R. W. Winzenried, Terra Tek
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APPENDIX C

DRILL-BIT PROGRAM PARTICIPANTS

DRILL-BIT FABRICATION

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