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ELEVATED TEMPERATURE FRACTURE TOUGHNESS AND
FATIGUE TESTING OF STEELS FOR GEOTHERMAL APPLICATIONS

Final Report

by

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Submitted to:

Brookhaven National Laboratory
Upton, Long Island, New York 11973

Attn: Dr. Daniel Van Rooyen

BNL Contract No. 492267-S

TR 81-97
October, 1981

TerraTek

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ABSTRACT

Conventional drill bit steels exhibit increased wear and decreased toughness when run at elevated temperatures in geothermal wells. Bits are therefore run at lower speeds and lighter loads, resulting in lower penetration rates for geothermal drilling than for conventional rock drilling.

Carpenter EX-00053, Timken CBS 600, Timken CBS 1000M and Vasco X-2M steels with improved hot hardness (improved wear resistance), were tested in conjunction with the steels used for cones (AISI 4820, 9315 and EX55) and lugs (AISI 8620, 9315 and EX55) in conventional roller cone rock bits. Short-rod fracture toughness measurements were made on each of these steels between room temperature and 400°C. Fatigue crack resistance was determined at 300°C for high-temperature steels and at room temperature for conventional steels. Scanning electron microscopy analyses of the fractured short-rod specimens were correlated with observed crack behavior from the test records. Test results are discussed and steel selections made for improved geothermal bits.

Carpenter EX-00053 and Timken CBS 1000M steels meet all design requirements for use in stabilizers, lugs and cones at temperatures to 400°C. It is recommended that EX-00053 and CBS 1000M be manufactured for geothermal drilling at the Geysers site.

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INTRODUCTION

Current Geothermal Drilling Practice and Experience

Geothermal drilling is done almost exclusively with rolling cutter bits, 3-point stabilizers, and other conventional drilling equipment developed for oil and gas recovery, and for mining applications. Unfortunately, these components have not been optimized for higher temperature operation, and deliver only about one-fifth of their normal life (footage) when used in some geothermal applications[1]. Performance in geothermal wells is further reduced since lighter bit loads must be used to prevent cataclysmic bit failures, and to avoid unwanted deviations caused by worn stabilizers. The resulting lower penetration rate (one-third to one-half of normal in many cases) is of much greater economic importance than the cost of the bit, because of the high daily cost of the drill rig. A bit capable of doubling the penetration rate is worth eight times the cost of the conventional bit[2]. The time lost in "tripping" to replace the bit and stabilizers incurs high rig costs which exceed the cost of the replaceables by two to four times. The overall cost per foot can be reduced by 25 percent or more by the development of bits and stabilizers having service lives which are equivalent to those of conventional bits and stabilizers in nongeothermal use.

The most severe geothermal drilling environments are those involving air drilling into hot, hard, abrasive formations. Additional factors such as swelling, inclined bedding, and fractures can further slow the drilling process. Air drilling is necessary in highly fractured, subhydrostatic reservoirs to avoid "lost circulation", and to avoid permanent quenching of steam vents. The air provides very little cooling of the bit and stabilizers because (a) it has usually been heated to the formation temperature by the time it arrives at the bottom, and (b) its specific heat is much lower than

that of mud or water. Friction can heat localized areas of the bearings to temperatures far in excess of the formation temperature. Surface corrosion and stress corrosion cracking (hydrogen embrittlement) are generally insignificant to bit life in air-drilled geothermal wells. 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. The H₂S embrittlement problem usually decreases with increased temperature, evidenced by the fact that brittle failure of drill bits at the Geysers has been almost nonexistent[3].

Previous Terra Tek/DOE Geothermal Drill Bit Program Results

New steels and tungsten carbides for geothermal roller cone bits were evaluated by a combination of full-scale laboratory drilling tests under simulated geothermal conditions, field geothermal drilling, and material properties tests[3]. Three generations of bits were built and tested; the third-generation bits concluded successful field tests at the Geysers in September, 1978. These prototypes exhibited an improvement of 40 percent in bit life. The lack of suitable stabilizers precluded evaluation of higher bit weights, which would have demonstrated the full potential of the new bits.

The Drilling Research Laboratory, shown in Figure 1, was utilized for evaluation of all three generations of bits. The first two generations were run in the Geothermal Wellbore Simulator (Figure 2), while two of the third-generation bits were run in the Geothermal Air-Drilling Test Facility (Figure 3) prior to the field tests. A total of six third-generation bits were evaluated at the Geysers by Union Geothermal Division of Union Oil Company.

The first two generations of bits were fabricated by Reed Tool Company from tool steels which were known to retain hardness at temperatures to 400°C, such as H-13 (lugs), Vasco MA and Vasco X2 (cones), and M50 (bearings). Back-

Figure 1. The Drilling Research Laboratory.

Figure 2. Geothermal Wellbore Simulator.

Figure 3. The Geothermal Air-Drilling Test Facility.

to-back drilling tests with conventional bits in the Geothermal Wellbore Simulator at 316°C revealed an approximate ten-to-one reduction in bearing wear (Table 1). While these results clearly indicated the importance of retaining bearing race hardness at temperature, brittle failures of both cones and lugs were experienced, as shown in Figure 4.

Steels were sought for the third generation bits which could maintain high fracture toughness in addition to maintaining high hardness in the bearing races and high tensile strength to prevent rupture. Baseline fracture toughness tests on AISI 8620 (conventional lugs) and AISI 4820 (conventional cones) indicated toughness values of $135 \text{ MPa}\sqrt{\text{m}}$ ($123 \text{ ksi}\sqrt{\text{in}}$)* and $90 \text{ MPa}\sqrt{\text{m}}$ ($82 \text{ ksi}\sqrt{\text{in}}$) respectively. Steels were sought for the lugs and cones which could meet these fracture toughness requirements, with the highest attainable race hardness. The materials selections are shown in Figure 5. Laboratory determinations of fracture toughness for M50 rollers, shown in Figure 6, illustrate

*The 1-inch diameter sample used for the AISI 8620 was too small for a valid K_{IC} measurement, even with the "short-rod" method employed; the $135 \text{ MPa}\sqrt{\text{m}}$ figure is accurate to within ± 15 percent.

TABLE 1

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. Two measurements were made of tapered wear on both cones and bits. IN and OUT measurements are described in Figure 9 of Terra Tek Report TR 78-41.
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.

Figure 4. Brittle failure of H-13 lug.

Figure 5. Materials selected for the third-generation drill bits.

Figure 6. Fracture Toughness of the Roller Bearing Steels.

how some hardness was sacrificed to maximize fracture toughness. It is important to realize that the sacrifice of hardness does not always enhance the toughness of steels. Figure 7 plots fracture toughness as a function of temperature for the CBS 600 lug steel; these data were obtained using the "short-rod" technique with 50.8 mm diameter by 76.2 mm long samples. It should be noted that toughness decreases with increasing temperature for this steel, thus illustrating the importance of elevated-temperature toughness testing: all previously tested steels exhibited increasing toughness with increasing temperature. Figure 8 shows the desirable hot-hardness characteristics of CBS 600, as compared to AISI 8620.

Figure 7. Fracture Toughness at Temperature for CBS 600 Lug Steel At a Core Hardness of R_c 35.

Figure 8. Hardness versus Temperature for Bit Lug Materials (Timken Corporation).

Six of the third-generation bits were run at the Geysers by Union Geothermal; the prototypes were alternated with the Reed Y73-JA conventional bits which are geometrically identical. The bits drilled typical Geysers ("Franciscan") graywacke sandstone; the air entering the bits was at the formation temperature, i.e., about 240°C. A detailed post-mortem wear analysis (Figure 9) of the experimental and conventional bits revealed the superior performance of the third-generation bits.

Figure 9. Wear Data for Bits Tested at Geysers.

The following conclusions and observations on bearing wear were drawn from these drilling tests[3]:

- The use of CBS 600 reduced lug wear by about $2\frac{1}{2}$ to 1 in the ball and roller races, and on the pilot pins of the bits utilizing M50 bushings. Lug wear, although greatly improved, needs to be reduced further. Microhardness traces on sections of CBS-600 lugs indicated that surface temperatures exceeded 400°C on the roller and ball races, and 600°C under the Stellite on the end of the pilot pin. Deformation of the pilot pins was noted on the experimental bits but to a lesser extent than on the Y73JA's.
- CBS 600 should also be used for the cones.
- The M50 rollers experienced very minimal wear.
- The excessive ball wear was due to the design of the ball retainer plug; a definitive test of the M50 balls is still required. Good performance is expected, based on the low wear experienced by the M50 rollers.
- Overall wear in the pilot bearing system ("friction pin area") is excessive and should be reduced by a factor of three.

Current Research

The previous Terra Tek/DOE work greatly enhanced the understanding of the relationships between laboratory materials property tests and field drilling performance in the geothermal environment. Since conventional steels (AISI 4820, 8620, 9315 and EX55) fail by excessive wear rather than by brittle fracture in the field[3], it was determined that steels which have high hot hardness and hence superior resistance to wear at elevated temperatures should be the prime candidates for improved geothermal lugs and cones. The brittle fracture of the cones and lugs of the MK-II experimental bits, however, indicate the need for fracture toughness and fatigue crack resistance in the experimental steels at levels comparable to those of the conventional steels. Steels presently used in rock bits include AISI 4820, AISI 8620, AISI 9315 and EX55, a steel recently developed by Climax Molybdenum Company in conjunction with Hughes Tool Company. EX55 has increased hardenability, as compared to

AISI 4820, 8620 and 9315, which improves the yield strength and therefore improves carbide tooth retention in larger diameter bits[4]. These four steels were used to establish the fracture toughness of conventional drill bit steels. Three new candidate steels are listed in Table 2 along with CBS 600, which required further evaluation. Several modifications to the composition of CBS 1000 and one modification of AISI 9310 were made, based on initial fracture toughness data[5].

Table 2
Candidate High-Temperature Alloy Steels

Manufacturer	Alloy	Recommended by
Carpenter	EX-00053	Smith Tool Company
Teledyne-Vasco	X2 Modified	Terra Tek/DOE Program
Timken	CBS 1000M	Timken Research Center
Timken	CBS 600	Terra Tek/DOE Program

All of these steels are either in use, or under consideration, for applications where high-strength, high-temperature carburizing steels are required. These include: helicopter main drive gears, speed reducers for turboprops, jet helicopters, and gas-turbine truck engines, as well as afterburner and thrust reverser mechanisms for military aircraft. Nominal compositions for the high-temperature steels and for conventional steels are given in Table 3. Hardness of carburized cases and cores of all of these steels except AISI 4820 and EX55 are displayed in Figure 10 as a function of temperature. The hardness of 8620 and 9315 declines rapidly with increasing temperature in both the case and core, as opposed to the excellent retention of hardness in the experimental steels. Although manufacturer's hot-hardness data were not available for 4820, it is expected to behave similarly to 9315. CBS 1000M appears to have the highest hot hardness.

Table 3
Nominal Steel Compositions

Steel Type	Composition (% by weight)										
	C	Mn	P	S	Si	Cr	Ni	Mo	V	W	Cu
AISI 4820	0.20	0.60	0.035	0.040	0.28	--	3.50	0.25	--	--	--
AISI 8620	0.20	0.80	0.035	0.040	0.28	0.50	0.55	0.20	--	--	--
AISI 9315	0.15	0.55	0.025	0.025	0.28	1.20	3.25	0.12	--	--	--
EX55	0.17	0.88	0.010	0.011	0.33	0.50	1.80	0.73	--	--	--
CBS 600	0.20	0.55	--	--	1.05	1.45	--	1.00	--	--	--
CBS 1000M	0.13	0.50	--	--	0.50	1.05	3.00	4.50	--	--	--
EX-00053	0.10	0.35	--	--	1.00	1.00	2.00	3.25	0.10	--	2.00
Vasco X2M	0.13	0.25	--	--	1.00	5.20	0.06	1.30	0.40	1.35	--

Figure 10. Effect of Temperature on Hardness of Conventional and Experimental Steels.

The objectives of the present research were therefore to characterize the fracture toughness and fatigue behavior of steels presently used in rotary drill bits and reaming stabilizers and to identify highly wear-resistant steels with equivalent toughness and fatigue crack resistance at temperatures to 400°C. It was believed that wear-resistant steels with fracture toughness values at 200°C-400°C between 90 MPa√m (82 ksi√in) and 135 MPa√m (123 ksi√in) would have sufficient toughness to maintain high penetration rates in geothermal wells. The 90-135 MPa√m range was determined from a limited data bank of fracture toughness data for 4820 (cones) and 8620 (lugs) developed at Terra Tek[3]. The two steels which exhibited brittle failure in the MK-II bits had K_{IC} values between 25 and 65 MPa√m at temperatures up to 400°C[6].

EXPERIMENTAL PROCEDURE

Sample Preparation

AISI 4820: Test blanks 50.8 mm diameter by 76.2 mm long were machined from a 55 mm diameter forged and annealed rod 1.8 m in length. The steel was of aircraft quality and had been vacuum melted. The long axes of the blanks were parallel to the long axis of the rod.

AISI 8620: Cylinders 50.8 mm diameter by 76.2 mm long were made from an air-melted, hot-rolled bar 57.2 mm diameter by 1.8 m in length.

AISI 9315: Specimens 25.4 mm diameter by 38.1 mm long were cut from aircraft-quality, vacuum-arc-remelted steel rod. The hot-rolling direction was parallel to the long axes of the cylinders.

9310M: Specimens 25.4 mm diameter by 38.1 mm long were machined from air induction melted steel plate squares. The long axes of the specimens were parallel to the forging direction.

EX55: Cylinders 19.1 mm diameter by 28.6 mm long were machined from air induction melted forged bars, roughly 25.4 mm in diameter.

CBS 600: Cylinders 50.8 mm diameter by 76.2 mm long were machined from vacuum-arc-remelted, hot-rolled bar stock. The long axes of the specimens were parallel to the rolling direction. Test blanks 25.4 mm diameter by 38.1 mm long were made from a forged bar which was quartered before machining the cylinders. The long axes of the specimens were parallel to the long axis of the bar.

CBS 1000M: Test blanks 50.8 mm diameter by 76.2 mm long were turned from a hot-rolled 76.2 mm diameter bar. The steel had been vacuum induction melted and vacuum-arc-remelted (VIMVAR). Cylinders 25.4 mm diameter by 38.1 mm long of the same composition were cut from a second heat in an identical manner

except that the steel was machined to the smaller diameter. Two additional heats, coded CBS 1000M-3 and CBS 1000M-4, were made by air induction melting. Cylinders 25.4 mm diameter by 38.1 mm length were machined from rolled bar stock as described above.

EX-00053: A rough forged rod approximately 60 mm in diameter was machined into cylinders 50.8 mm diameter by 76.2 mm long. The steel was VIMVAR. Additional cylinders were cut from bars hot-rolled to different diameters. Test cylinders 19.1 mm diameter by 28.6 mm long were machined from a hot-rolled rod approximately 25.4 mm in diameter. Additional cylinders 50.8 mm diameter by 76.2 mm long were made from a hot-rolled rod 90 mm in diameter. All hot-rolled rods were rolled from 0.35-0.40 m diameter ingots.

X-2M: Vacuum-melted, hot-rolled bars were used to make cylinders 50.8 mm diameter by 76.2 mm long. The cylinder axes were parallel to the rolling direction. Test blanks 25.4 mm diameter by 38.1 mm long were made from other heats in a similar manner.

Ladle analyses of 4820, 8620 and EX-00053, as well as the chemical composition of the 19.1 mm and 25.4 mm cylinders of EX55, 9315, X-2M, CBS 600 and CBS 1000M, are listed in Table 4. Detailed heat treatments of each of the steels appear in Appendix A. A grip groove was machined into the end of each specimen, as illustrated in Figure 11. Thin slots were machined longitudinally in the 50.8 mm cylinders and cut with a diamond saw for 19.1 and 25.4 mm cylinders, leaving a "V"-shaped ligament in the intended crack plane.

Testing and Data Reduction

Fracture Toughness: The short-rod method[7] was used to measure the fracture toughness of the steels at various temperatures. The theory for this novel technique has been developed for materials displaying linear elastic fracture mechanics (LEFM)[8] and non-LEFM[9]. Comparisons of the short-rod

Table 4

Ladle and Check Analyses of Steels

Steel Type	Manufacturer's Code	C	Mn	P	S	Si	Cr	Ni	Mo	V	W	Cu	Al	Melt Practice
AISI 4820 ^a	--	0.18	0.65	0.012	0.013	0.26	0.15	3.30	0.25	--	--	0.08	--	V ¹
AISI 8620 ^a	--	0.19	0.74	0.013	0.021	0.21	0.48	0.47	0.18	--	--	0.04	0.050	Ind. ²
AISI 9315 ^b	9315	0.13	0.59	0.009	0.006	0.31	1.31	3.28	0.12	--	--	--	0.030	Ind.
9310M ^b	X677	0.09	0.45	0.005	0.020	0.18	1.08	2.29	0.13	0.007	--	--	0.016	Ind.
EX55 ^b	--	0.17	0.84	0.010	0.017	0.21	0.58	1.77	0.69	--	--	--	--	Ind.
CBS 600 - #1 ^b	3,4	0.20	0.71	--	--	1.21	1.38	--	1.02	--	--	--	--	VAR ³
CBS 600 - #2 ^b	600	0.20	0.60	0.004	0.004	1.01	1.55	0.06	0.97	--	--	--	0.036	VAR
CBS 600M - #1 ^b	671	0.19	0.66	--	--	0.92	1.35	1.92	0.94	--	--	--	0.037	Ind.
CBS 600M - #2 ^b	672	0.19	0.66	--	--	1.01	1.42	1.46	0.94	--	--	--	0.033	Ind.
CBS 1000M - #1 ^b	1,2	0.14	0.57	--	--	0.50	0.80	3.20	4.13	0.32	--	--	--	VIMVAR ⁴
CBS 1000M - #2 ^b	2, 3A, 3B	0.13	0.54	0.008	0.007	0.38	1.01	3.05	4.47	0.39	--	--	0.035	VIMVAR
CBS 1000M - #3 ^b	X676	0.08	0.47	0.010	0.024	0.23	0.95	2.87	3.83	0.15	--	--	0.033	Ind.
CBS 1000M - #4 ^b	X678	0.09	0.51	0.010	0.022	0.87	0.97	1.91	3.16	0.11	--	--	0.027	Ind.
EX-00053 - #1 ^a	K97183	0.103	0.33	0.007	0.006	0.95	0.99	2.03	3.32	0.11	--	2.06	--	VIMVAR
EX-00053 - #2 ^a	K81877	0.086	0.33	0.011	0.003	0.96	1.05	2.01	3.25	0.10	--	2.19	--	VIMVAR
VASCO X-2M - #1 ^b	3898A	0.13	0.29	0.007	0.002	0.98	4.80	--	1.40	0.47	1.46	--	--	VAR
VASCO X-2M - #2 ^b	3801A	0.16	0.31	0.009	0.003	0.99	4.90	--	1.40	0.45	1.36	--	--	VAR

^aLadle Analysis; ^bChemical composition of test cylinders; ¹Vacuum melted; ²Air induction melted

³Vacuum arc remelted; ⁴Vacuum induction melted and vacuum arc remelted

Figure 11. Short-Rod Specimen Geometry.

technique with the standard ASTM E399 method of measuring fracture toughness have shown good agreement[10], as have different techniques for calibrating the short-rod specimens[11,12]. Although several advantages of the short-rod method have become apparent[13], the main reason for using the technique to evaluate drill bit materials is that specimen diameters similar to the through-section thickness of cones or lugs can be tested. Diameters as small as $1.0 (K_{IC}/\sigma_{ys})^2$ (where K_{IC} is the toughness and σ_{ys} is the yield strength of the steel) can be tested by the short-rod technique whereas the thickness of the ASTM E399 compact toughness specimen must be at least $2.5 (K_{IC}/\sigma_{ys})^2$ [9].

Several loading devices have been developed for short-rod testing including a machine called a "fracjack", shown in Figure 12. The fracjack is installed in a tensile testing machine (Figure 13). The specimen is placed over the grips on the fracjack (Figure 14) and a copper chamber with cartridge heaters is installed over the specimen (Figure 15). A thermocouple, placed in the chevron-shaped slot, is connected to a controller which supplies power to

Figure 12. Fracjack loading device with specimen installed over grips.

Figure 13. Fracjack located in tensile testing machine.

Figure 14. Installation of a specimen on the fracjack grips. The short-rod sample is shown installed on grips which have been removed from the fracjack.

Figure 15. Installation of the temperature control chamber over a short-rod.

the heater cartridges. For specimens tested at elevated temperatures, the chamber was installed, brought to the desired temperature and then held five minutes before applying a load. The equipment used to test 50.8 mm diameter short-rod samples is shown in Figure 16.

Specimens having diameters less than or equal to 25.4 mm were tested in a Fractometer II test machine[13] which employs smaller grips and a smaller heater. Actuating the test machine (Figure 16) causes the grips to force the specimen mouth open. The fracjack rotates the grips as the specimen mouth is opened, which results in lines of constant load between the grips and the inside surfaces of the specimen mouth. The load applied to the specimen is plotted as a function of the mouth opening or Load Point Opening (LPO), as seen in Figure 17. The initial loading slope is linear, as the mouth of the specimen is elastically opened by the grips. Eventually, the load-LPO trace deviates from linearity, indicating that a crack has initiated at the point of the V. Increasing the load causes stable crack growth which constantly widens the crack front. The fracture toughness measurement is made in the region of the maximum load after the crack has grown into the central region of the specimen. The load is released and reapplied several times during the test (two unloading-reloading sequences are seen in the test record in Figure 17) to determine and correct for residual stresses and plasticity. In several of the steel specimens tested, the plastic zone associated with the crack tip was appreciable, causing the stretched material within the zone to prop the mouth slightly open after the external load was released. The degree of plasticity is easily determined from the test record and the effect of the plastic zone on the indicated toughness is known[9].

Macroscopic residual stresses also affect the measurement of the fracture toughness by causing the test crack to be in a state of tension or compression

Figure 16. Tensile testing machine, control panel and temperature controller used for short-rod fracture toughness and fatigue measurements.

Figure 17. Load Versus LPO Test Record for a Steel Sample with Minimal Plasticity.

before the application of any external load. The effects of residual stresses in short-rod specimens can be detected and compensated for in much the same manner as the specimen plasticity is measured[14].

In some cases, the phenomenon of crack closure[15] causes the unloading paths to become nonlinear after most of the unloading has occurred. Crack closure is caused by material on the crack surfaces which has been pulled out or disturbed during fracture to partially fill the space between the two fractured surfaces. The steepening of the unloading paths resulting from the early closure of the crack does not affect the fracture toughness measurement but does limit the range in which loads can be applied during fatigue testing.

Several of the specimens tested exhibited "crack-jump behavior" rather than the smooth crack growth just described. These specimens had load-displacement test records which consisted of a few very rapid jumps in crack position. Each crack jump was accompanied by an audible "pop" and a decrease in the applied loading force. Between the jumps, as loading continued, the crack was nearly stationary until the load was increased to a level which

precipitated the next jump. Although specimens displaying crack-jump behavior do not allow for unloading-reloading cycles so that the effects of plasticity or residual stress can be included in the determination of fracture toughness, they do provide insight into the mode of fracture, as discussed later (see Steel Characterization Section). The loading sequence of the short-rod fracture toughness test was completed in less than one minute for specimens exhibiting either smooth crack growth or crack-jump behavior.

Fatigue Crack Resistance Measurements

Specimens identical to those used in static fracture toughness measurements were used to determine the fatigue behavior of the steels. Fatigue tests were initially performed at room temperature for AISI 4820, 8620 and 9315, and at 300°C for CBS 600-#1, CBS 1000M-#1, EX-00053#1 and Vasco X-2M-#5. Cylinders 50.8 mm in diameter were used for all steels except 9315, for which 25.4 mm diameter specimens were tested. All measurements were made in air and although the humidity was not monitored, it was relatively constant near 25 percent.

A Textronix 531A oscilloscope was used to monitor the load-displacement behavior for all fatigue testing and a Polaroid camera made permanent record of the tests. The sample was placed in the fracjack loading device then the appropriate temperature was obtained and monitored throughout the test. The specimen was initially loaded and the slope of the load-displacement line recorded. The specimen was then further loaded to initiate a crack before fatigue cycling began. All samples were cycled at 5 Hz using a sinusoidal wave with the specimens being loaded and unloaded in tension. The initial minimum and maximum loads were not identical for all samples since crack closure effects varied and it was necessary to avoid crack closure in all instances.

After the crack was initiated, the specimen was cycled between two constant loads and the average difference between the loads was used to determine an average ΔK ($K_{\max} - K_{\min}$) in an identical manner to that used in static fracture toughness tests[9]. Crack advance was measured using previously determined compliance calibrations[11,12] by correlating the change in the slope of the load-displacement curves from the oscilloscope with the initial crack length and loading slope determined at the beginning of the test. The maximum load was increased periodically throughout the test, thereby increasing ΔK and allowing several ΔK values to be measured from one sample. The loading-unloading slope, and hence the change in compliance as well as the number of cycles, were recorded each time just before the load was increased. A typical test consisted of approximately 100,000 cycles and five to ten ΔK levels. A plot of the rate of crack growth as a function of the change in toughness was made by applying the Paris power law[16]:

$$\frac{da}{dN} = C(\Delta K)^m \quad (1)$$

where da/dN is the fatigue crack growth rate, ΔK is the cyclic stress intensity ($\Delta K = K_{\max} - K_{\min}$) and C and m are material constants dependent on frequency, temperature, environment and stress ratio. To eliminate the effect on the data of changing stress ratio[17], the following relationship was used[18]:

$$\frac{da}{dN} = \frac{C(\Delta K)^m}{\sqrt{1-R}} \quad (2)$$

where R is the stress ratio ($R = K_{\min}/K_{\max}$). The fatigue crack growth at a specific ΔK was determined by dividing the change in crack length (Δa) by the number of cycles (ΔN) recorded during the constant ΔK period of the test.

Additional fatigue tests were performed using 25.4 mm diameter cylinders of AISI 9315, CBS 600-#2, CBS 1000M-#2 and Vasco X-2M-#2. These fatigue tests were conducted at room temperature (22°C) for all of the steels, and also at

300°C for Vasco X-2M-#2. The relative humidity was monitored during all tests. The geometry of the specimens was the same as that used for short-rod fracture toughness testing. A Textronix T935 X-Y oscilloscope was used to monitor the load-displacement behavior of the specimen during testing. The slope of the initial load-displacement trace was recorded on a Hewlett-Packard X-Y recorder. The specimen was further loaded, as described above, to initiate a crack before fatigue cycling began. These samples were cycled at 10 Hz with the specimens being loaded and unloaded in tension. Periodically throughout the test, the frequency was reduced to 0.1 Hz while a load-displacement trace was recorded and then increased again to 10 Hz. The time that the specimen was cycled at 0.1 Hz was less than 30 seconds for each recording. The crack advance was determined using the most recent compliance calibration data for the short-rod geometry[19]. Data were analyzed by the modified Paris power law (Equation 2) as described above.

STEEL CHARACTERIZATION

Radian Corporation, with support from DOE/DGE Chicago Operations Program, analyzed each of the steels tested during the first year of the program, with results displayed in Table 5. The chemical analyses performed by the Timken Company for CBS 600-#2, CBS 1000M-#2 and 9315 (see Table 4) agree well with the Radian results except for the nickel content of 9315. The chemical analysis performed by Teledyne Vasco for X-2M-#1 (see Table 4) also agree with the Radian analysis except that the tungsten content as determined by Radian Corporation is very low.

Radian Corporation also measured the hardness (Rockwell C) of the fractured steel specimens. Decarburization was noted on the surface of several of the samples, but this had no effect on toughness or fatigue measurements because of the configuration of the test specimens. Hardness measurements were made at approximately every 1.6 mm from the surface to the center of each specimen, with results shown in Table 6. The bracketed hardness value best

Table 5

Chemical Analysis Performed by Radian Corporation
(Percent by Weight)

Steel Type	C	Mn	P	S	Si	Cr	Ni	Mo	V	W	Cu
4820	0.18	0.63	0.008	0.013	0.29	--	3.31	0.22	--	--	--
8620	0.20	0.75	0.007	0.017	0.19	0.49	0.46	0.18	--	--	--
9315	0.12	0.58	0.009	0.006	0.31	1.31	3.44	0.17	--	--	--
CBS 600-#1	0.20	0.71	--	--	1.21	1.38	--	1.02	--	--	--
CBS 600-#2	0.19	0.63	0.008	0.006	1.06	1.58	--	1.04	--	--	--
CBS 1000M-#1	0.14	0.57	--	--	0.50	0.80	3.20	4.13	0.32	--	--
CBS 1000M-#2	0.15	0.62	0.011	0.005	0.51	1.07	3.32	4.40	0.34	--	--
EX-00053-#1	0.093	0.30	--	--	0.99	0.81	2.05	3.15	0.09	--	1.81
X-2M-#1	0.13	0.21	--	--	0.99	4.49	0.05	1.28	0.36	0.72	--

Table 6
Characterization of Steels

Steel Type	Heat* Treat- ment	Core Hardness (R_c)	Grain Size (McQuaid Ehn)	Yield Strength (2% Offset)†		Tensile† Strength	
				MPa	ksi	MPa	ksi
4820	A	37.0-42.5 (38.0)	8-9	869	126	1,172	170
8620	B	20.5-28.5 (22.0)	7-8	827	120	1,151	167
9315	C	34.0-39.5 (35.5)	7	848	123	1,096	159
CBS 600-#1	F	37.5-39.0 (38.0)	6	1,262	183	1,172	170
CBS 600-#2	F	39.0-41.0 (39.0)	6	1,262	183	1,172	170
CBS 1000M-#1	I	37.0-40.0 (38.5)	5-6	1,200	174	1,462	212
CBS 1000M-#2	K	36.5-39.5 (38.5)	6	1,200	174	1,462	212
EX-00053-#1	P	31.5-35.0 (32.0)	Finer than 10	965	140	1,159	168
X-2M-#1	R	37.5-40.0 (38.5)	8-9	1,034	150	1,379	200

*See Appendix A for explanation of heat treatment code.

†Manufacturer's data.

describes the hardness in the center of the specimen. The Timken Company measured the surface hardness of test cylinders after heat treatment and found values of R_c 41.5 for 25.4 mm and R_c 38 for 50.8 mm specimens. The hardness at the center of CBS 600 specimens, as determined by Radian, was R_c 38.0 for CBS 600-#1 and R_c 39.0 for CBS 600-#2 specimens. Timken measured a surface hardness of R_c 37 for CBS 1000M-#1 specimens and R_c 43.0 for the same heat treatment of CBS-1000-#2 specimens. Radian measurements indicated essentially identical hardness values for the two heats.

McQuaid-Ehn grain size (ASTM E112 A.3.2.1.1-78) as determined by Radian Corporation is listed in Table 6. This procedure is based on determining the austenite grain size after carburization and does not necessarily produce a valid measure of the prior austenite grain size in specimens in the condition in which they were tested. The only conclusion that can be derived from the

McQuaid-Ehn grain size measurements is that the Carpenter EX-00053 steel has a very fine grain size.

Radian determined that the microstructures of 9315, EX-00053-#1 and X-2M-#1, after the treatments listed in Appendix A, consist entirely of tempered martensite. Continuous cooling transformation diagrams[20] predict a microstructure consisting of nearly 100 percent bainite with a trace of martensite for a 50.8 mm diameter 4820 rod water quenched from 780°C and an identical cylinder made of 8620 should have a microstructure at the center consisting of about 50 percent ferrite, 45 percent bainite and 5 percent martensite after water quenching from 830°C. It is apparent that the microstructures of 4820 and 8620 will vary over the width of the crack in a short-rod specimen and that characterization of the grain size and microstructure in these steels is important. Tabulation of the yield strength and tensile strength of steels, based on manufacturer's data in Table 6, indicates that each of the candidate steels have higher strengths than the conventional steels presently in use.

Scanning electron microscopy (SEM) of the fractured surfaces was performed by Radian Corporation. Selected micrographs are displayed in Appendix B (Figures B1 through B18). The SEM micrographs seen in Figures B19 through B32 represent comparison fracture surfaces from static and fatigue test samples and were taken by Terra Tek at the University of Utah. The fracture mode was transgranular for all specimens. The degree of ductility estimated by Radian from their SEM micrographs is listed in Table 7. Also included in Table 7 is the observed crack behavior from load-displacement test records. It is interesting to note that the brittle-to-ductile transitions noted in CBS 1000M-#1, EX-00053-#1 and X-2M-#1 between room temperature and 200°C correlate well with the observed crack behavior from the test records. There is, however, no information from the SEM micrographs to explain the crack jump behavior observed in 8620, 9315, CBS 600-#2 and CBS 1000M-#2 at high temperatures.

Table 7
Fracture Mode Based on SEM Micrographs

Steel Type	Fracture Temperature (°C)	Degree of Ductility	Crack Behavior
4820	RT†	A	S
	100	A	S
	200	A	S
	300	A	S
8620	RT	C	S
	100	B	S
	200	A	S
	300	A	S-J
9315	RT	A	S
	100	A	S
	200	A	S
	300	A	S-J
CBS 600-#2	RT	A	S
	100	A	S
	200	A	S
	300	A	S
	400	A	J
CBS 1000M-#2	RT	D	J
	100	A	S
	200	A	S
	300	A	S
	400	A	J
EX-00053-#1	RT	B	J
	100	A	S
	200	A	S
	300	A	S
	400	A	S
X-2M-#1	RT	E	J
	100	E	J
	200	B	S
	300	A	S
	400	A	S

†RT - Room Temperature

A - Ductile, microvoid coalescence	S - Smooth Crack Growth
B - Mixed Mode, less than 25% brittle cleavage	J - Crack Jump Behavior
C - Mixed Mode, 25-75% brittle cleavage	S-J - Borderline Between Smooth and Crack Jump
D - Mixed Mode, greater than 75% brittle cleavage	
E - Brittle Cleavage	

Further characterization of the steels was performed at the University of Michigan. AISI 4820, 8620, 9315, EX55, CBS 600M-#2, CBS 1000M-#2 (heat treatment K), EX-00053-#1 (50.8 mm), EX-00053-#2 (heat treatment P), EX-00053-#1 (25.4 mm) and Vasco X-2M-#1 (heat treatment R) were evaluated to determine their hardness, prior austenite grain size and microstructure. The hardness of each of the ten specimens was measured along a radial line from the surface to the center of the sectioned short rod specimens. The results, as displayed in Appendix B, indicate slight decarburization on the surface of most of the steels. The hardness measurements appear consistent with values measured by the steel suppliers except for CBS 600M-2 and CBS 1000M-#2 for which values of R_C 43.5 and R_C 43.0 respectively were reported by Timken. Hardness measurements made at Terra Tek on CBS 600M-#2 gave a mean value of R_C 43.3 and R_C 40.3 for CBS 1000M-#2. Hardness measurements performed by steel suppliers were compared with measurements made at the University of Michigan, Terra Tek and Radian Corporation with the most consistent hardness results for each steel type reported in Table 8. Yield strength was estimated from data supplied by steel manufacturers and by Fopiano, et al[21], for Vasco X-2M.

Sectioned short rod specimens were held at 510°C for 14 hours before cooling in air in order to establish a temper embrittlement network in the austenite boundaries. The specimens were then polished and etched in a hot, saturated aqueous picric acid solution, then lightly re-polished. This procedure succeeded in revealing the grain size of 4820, 8620 and 9315, but EX55, CBS 600M-#2, CBS 1000M-#2 (heat treatment K), EX-00053-#1 (50.8 mm), EX-00053-#2 (heat treatment P), EX-00053-#1 (25.4 mm) and Vasco X-2M-#1 did not respond. The latter steels were repolished and etched in 4% or 10% nital, but definitive grain boundaries were only obtained in CBS 1000M. The grain size of X-2M was revealed by a $FeCl_3$ etch.

Table 8
Properties of Test Cylinders

Steel Type	Manufacturer's Code	Heat Treatment Code*	Specimen Diameter (mm)	Hardness, R _C		Estimated† Yield Strength (MPa)	Prior Austenite ASTM Grain Size
				x	σ		
4820	--	A	50.8	41.3	0.89		
8620	--	B	50.8	58.8 R _A	0.87 R _A	870	10-11
9315	--	C	25.4	41.3	1.5	825	9-10
9310M	X677	D	25.4	32-34†	--	850	10-11
EX55	--	E	19.1	42.3	0.52	--	--
CBS 600-#1	3	F	50.8	38.4	0.77	1100	8.8†
CBS 600-#1	4	H	50.8	44.6	1.1	1260	--
CBS 600-#2	600	F	25.4	40.1	0.60	1260	7-8†
CBS 600M-#1	671	G	25.4	43.5†	--	1260	7†
CBS 600M-#2	672	G	25.4	43.5†	--	--	--
CBS 1000M-#1	1	I	50.8	38.2	1.2	--	--
CBS 1000M-#1	2	J	50.8	42.7	0.26	1200	--
CBS 1000M-#2	2	K	25.4	39.8	1.2	1200	--
CBS 1000M-#2	3A	L	25.4	43.5†	--	1200	6
CBS 1000M-#2	3B	M	25.4	43.3	0.92	1200	--
CBS 1000M-#3	X676	N	25.4	35.5-37.5†	--	1200	--
CBS 1000M-#3	X676	O	25.4	32-34†	--	--	--
CBS 1000M-#4	X678	N	25.4	38-39†	--	--	--
CBS 1000M-#4	X678	O	25.4	36-38†	--	--	--
EX-00053-#1	--	P	50.8	36.0†	--	--	--
EX-00053-#2	--	P	50.8	34.5†	0.55†	965	--
EX-00053-#2	--	Q	50.8	32-34†	--	915	--
EX-00053-#1	--	P	25.4	37.3†	1.5†	860	--
Vasco X-2M-#1	--	R	50.8	41.5	0.89	1010	--
Vasco X-2M-#1	1-3	S	50.8	42.3	0.85	1035	7-8
Vasco X-2M-#1	4-6	T	50.8	41.4	0.62	1100	--
Vasco X-2M-#1	7-9	U	50.8	38.13	0.70	1035	--
Vasco X-2M-#1	10-12	V	50.8	35.0	0.35	930	--
Vasco X-2M-#1	13-15	UU	50.8	--	--	860	--
Vasco X-2M-#2	46-60	W	25.4	40.71	0.17	--	--
Vasco X-2M-#2	31-45	X	25.4	34.90	0.66	900	--
Vasco X-2M-#2	16-30	Y	25.4	30.00	0.50	860	--
Vasco X-2M-#2	1-5	Z	25.4	25.57	0.49	830	--
						760	--

*See Appendix A for explanation of heat treatment code.

†Data supplied by manufacturer.

An ASTM austenite grain size of 10-11, as illustrated in Figure 18A, was determined for 4820. The microstructure (Figure 18B) was mainly bainite, with a few volume percent ferrite. A grain size of 9-10 was measured for 8620 (see Figure 19A) while its structure consisted of a large fraction of ferrite, approaching 50%, as shown in Figure 19B. The grain size of 9315 was 10-11 (Figure 20A). Its microstructure consisted largely of tempered martensite with some bainite (Figure 20B). The microstructure of EX55, as shown in Figure 21, was mainly tempered martensite.

CBS 600-#2 specimens, quenched from 835°C (heat treatment F), when etched in 4% nital, displayed a grain size of 7 and a duplex microstructure consisting of tempered martensite with 40% acicular ferrite (Figure 22A). When a similar composition, CBS 600-#1, was austenitized at 870°C (heat treatment H), the microstructure was entirely tempered martensite and the grain size was 7-8 (Figure 22B). The microstructure of CBS 600M-#2 austenitized at 845°C (heat treatment G) was also largely tempered martensite (Figure 22C).

A prior austenite grain size of 6 was measured for CBS 1000M-#2 (heat treatment K), after etching in 4% nital, as illustrated in Figure 23A while the microstructure consisted largely of tempered martensite with M_6C carbides (Figure 23B).

No etching techniques were successful in revealing the austenite grain size of Carpenter's EX-00053 steel, but it is considerably finer than 10, based on the McQuaid-Ehn measurements discussed earlier. The microstructure in all three EX-00053 steels analyzed consisted largely of tempered martensite (Figures 24A-24C).

Prior austenite and ferrite grain boundaries in Vasco X-2M-#1 (heat treatment R) were revealed by etching with $FeCl_3$. The grain size was 7-8 (Figure 25A). This steel (Figure 25B) had a duplex structure composed of

Figure 18A. Prior Austenite Grain Boundaries in AISI 4820 (Heat Treatment A). G.S. 10-11, aqueous picric acid etch (500X).

Figure 18B. Microstructure of AISI 4820 (Heat Treatment A), 4% Nital Etch (250X).

Figure 19A. Prior Austenite Grain Boundaries in AISI 8620 (Heat Treatment B), G.S. 9-10, aqueous picric acid etch (500X).

Figure 19B. Microstructure of AISI 8620 (Heat Treatment B), 4% Nital Etch (250X).

Figure 20A. Prior Austenite Grain Boundaries in AISI 9315 (Heat Treatment C). G.S. 10-11, aqueous picric acid etch (500X).

Figure 20B. Microstructure of AISI 9315 (Heat Treatment C), 4% Nital Etch (250X).

Figure 21. Microstructure of EX55 (Heat Treatment E), 4% Nital Etch (250X).

Figure 22A. Microstructure of CBS 600-#2 (Heat Treatment F). G.S.7, 4% Nital etch (500X). Courtesy C. F. Jatczak, Timken Co.

Figure 22B. Microstructure of CBS 600-#1 (Heat Treatment H). G.S. 7/8, 4% Nital etch (500X). Courtesy C. F. Jatczak, Timken Co.

Figure 22C. Microstructure of CBS 600M-#2 (Heat Treatment G), 4% Nital Etch (250X).

Figure 23A. Prior Austenite Grain Boundaries in CBS 1000M-#2 (Heat Treatment K). G.S. 6, 4% Nital etch (250X).

Figure 23B. Microstructure of CBS 1000M-#2 (Heat Treatment K), 4% Nital Etch (250X).

Figure 24A. Microstructure of EX-00053-#1 (Heat Treatment P), 4% Nital Etch (250X).

Figure 24B. Microstructure of EX-00053-#2, 50.8 mm diameter (Heat Treatment P), 4% Nital Etch (250X).

Figure 24C. Microstructure of EX-00053-#2, 19.1 mm Diameter (Heat Treatment P), 4% Nital Etch (250X).

ferrite plus tempered martensite, indicating incomplete transformation to austenite before quenching. The effect of austenitizing temperature on ferrite content is seen in Figures 25C-25F. Vasco X-2M-#1, hardened at 1120°C (heat treatment S), had a duplex microstructure, largely martensite with approximately 10% ferrite (Figure 25C). The same steel hardened at 1065°C (heat treatment T), contained more ferrite (approximately 25%), but had a finer grain size (Figure 25D) than its counterpart austenitized at 1120°C. As the austenitizing temperature was decreased to 1010°C (heat treatment U) and 955°C (heat treatment V) the grain size decreased and the ferrite content increased, as illustrated in Figures 25E and 25F respectively.

Vasco X-2M-#2 steels, which have a slightly higher carbon content than Vasco X-2M-#1 steels (0.16 versus 0.13%C), showed a similar change in microstructure with hardening temperature. The grain size decreased and the fer-

rite content increased as the austenitizing temperature was lowered, as illustrated in Figure 25G (980°C, heat treatment W), Figure 25H (955°C, heat treatment X), Figure 25I (925°C, heat treatment Y) and Figure 25J (900°C, heat treatment Z). It is interesting to compare Figures 25F and 25H since they reveal the microstructure of Vasco X-2M-#1 and X-2M-#2 respectively, austenitized at 955°C. Fopiano, et al[21] showed that the amount of primary ferrite decreased with increasing austenitizing temperature and increasing carbon content. As expected, the steel with the lower carbon content (X-2M-#1) contained more ferrite at the same hardening temperature. The effect of increasing primary ferrite on hardness is demonstrated by the decrease in hardness with decreasing austenitizing temperature, as seen in Table 8.

Figure 25A. Prior Austenite and Ferrite Grain Boundaries in Vasco X-2M-#1 (Heat Treatment R). G.S. 7/8, FeCl_3 etch (250X).

Figure 25B. Microstructure of Vasco X-2M-#1 (Heat Treatment R), 10% Nital Etch (250X).

Figure 25C. Microstructure of Vasco X-2M-#1 (Heat Treatment S), 2% Nital Etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

Figure 25D. Microstructure of Vasco X-2M-#1 (Heat Treatment T), 2% Nital etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

Figure 25E. Microstructure of Vasco X-2M-#1 (Heat Treatment U), 2% Nital Etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

Figure 25F. Microstructure of Vasco X-2M-#1 (Heat Treatment V), 2% Nital Etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

Figure 25G. Microstructure of Vasco X-2M-#2 (Heat Treatment W), 2% Nital Etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

Figure 25H. Microstructure of Vasco X-2M-#2 (Heat Treatment X), 2% Nital Etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

Figure 25I. Microstructure of Vasco X-2M-#2 (Heat Treatment Y), 2% Nital Etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

Figure 25J. Microstructure of Vasco X-2M-#2 (Heat Treatment Z), 2% Nital Etch (500X). Courtesy R.J. Henry, Teledyne/Vasco.

71. The following information was obtained from the 1973-1974
survey of the population of the United States.

72. The following information was obtained from the 1973-1974
survey of the population of the United States.

RESULTS AND DISCUSSION

Fracture Toughness

AISI 4820: The toughness of 4820 (heat treatment A) as a function of temperature is listed in Table 9 and shown in Figure 26. The steel was tested with slots and grip grooves machined before heat treating, and also as machined after heat treating, with no observed difference in the fracture toughness. The fracture toughness declines steadily with temperature to 200°C and then increases slightly between 200 and 300°C. SEM micrographs revealed dimpled rupture indicative of ductile fracture at all temperatures. Although there is no obvious reason for the decrease in toughness with temperature, the increase above 200°C may be due to microstructural changes occurring during the test, because the tempering temperature was only 230°C[22]. The important observation is that the toughness at 200°C is only half the value of the fracture toughness at room temperature.

AISI 8620: The low hardenability of 8260 (heat treatment B), relative to other steels tested, caused differences in the fracture toughness depending on whether the cylinders were slotted before or after heat treating (see Table 9 and Figure 27). The specimens heat treated after slotting showed considerable scatter between tests due to residual stresses arising from quenching and phase transformation. The specimens quenched without slots displayed consistently higher toughness at room temperature and 300°C than their slotted counterparts, but no difference was observed at 100°C and 200°C. As for 4820, the 300°C test temperature exceeded the 230°C tempering temperature, so microstructural changes during the test were inevitable.

The obvious trend, regardless of the timing of slot cutting, is a drop in toughness with temperature, despite the fact that the SEM micrographs indicate some degree of brittle cleavage at both room temperature and 100°C and ductile

Table 9

Fracture Toughness of Conventional Type Drill Bit Steels

Steel Type	Specimen Diameter (mm)	Heat Treatment Code*	Test Temperature (°C)	K_{IcSR}^{**} (MPa√m)			
				Individual Values	Mean	Standard Deviation	Coefficient of Variation
4820	50.8	A	22	100.2†, 71.4†, 93.4, 109.2, 103.6	95.6	14.6	15.4
			100	78.8†, 81.3†, 76.2	78.8	2.53	3.2
			200	50.8†, 48.5†, 58.0, 66.9, 62.5	57.2	7.81	13.6
			300	68.9†, 65.9†, 67.8	67.5	1.54	2.2
8620	50.8	B	22	108.0†, 85.3†, 127.9, 128.7	112.5	20.6	18.2
			100	98.7†, 99.7†, 107.8, 89.7	99.0	7.48	7.5
			200	72.7†, 73.2†, 75.2	73.7	1.32	1.8
			300	55.8†, 64.9†, 78.8, 76.7	69.1	10.8	15.6
9315	25.4	C	22	124.3, 121.2, 116.9	120.8	3.74	3.1
			100	103.1, 110.8, 112.1	108.7	4.84	4.5
			200	90.8, 95.3, 100.3	95.5	4.84	4.4
			300	81.8, 88.4, 84.5, 91.6	88.0	2.97	3.4
			400	93.8, 95.7, 95.9, 92.4	95.2	1.10	1.2
9310M	25.4	D	22	123.0, 127.6	125.3	3.21	2.6
			100	110.7, 112.8	111.8	1.45	1.3
			200	92.1, 84.5	88.3	5.37	6.1
			300	75.3, 76.7	76.7	2.09	2.7
			400	79.8, 74.3	77.0	3.91	5.1
EX55	19.1	E	22	74.4, 68.9, 89.0, 69.2, 77.0	75.7	8.20	10.8
			100	72.3, 64.6, 71.5	69.5	4.23	6.1
			200	65.0, 64.9, 63.5	64.5	0.83	1.3
			300	59.2, 64.0, 57.8, 75.7	64.2	8.09	12.6
			375	58.4, 62.8	60.6	3.09	5.1
			385	65.9, 66.5	66.2	0.44	0.7
			400	80.2, 66.4, 70.4, 67.3	71.1	6.35	8.9

*See Appendix A for explanation of heat treatment code.

†Specimens slotted before heat treating (all others slotted after heat treating).

**Plane-strain fracture toughness as measured by the short rod technique.

Figure 26. Fracture Toughness as a Function of Temperature for 4820 (Heat Treatment A).

Figure 27. Effect of Temperature on the Toughness of 8620 (Heat Treatment B).

fracture by microvoid coalescence at temperatures of 200°C and 300°C. The most serious problem with 4820 and 8620, however, is the drop in hardness between ambient and 200°C, since wear is greatly accelerated in these steels by increased temperature.

AISI 9315: The 9315 steel (heat treatment C), with its entirely martensitic structure, high nickel content and low carbon content, displayed the best toughness of any of the conventional steels tested. The toughness decreased only from 120.7 MPa√m at room temperature to 88.0 MPa√m at 300°C, as displayed in Figure 28. The fracture toughness of 9315 is adequate over the entire temperature range and the only drawback to this steel is its poor wear resistance (low hardness) at elevated temperatures (see Figure 10) in comparison to the candidate steels in the program. As for 8620 and 4820, the test temperatures considerably exceeded the tempering temperature of 175°C.

Figure 28. Fracture Toughness of 9315 (Heat Treatment C) and 9310M (Heat Treatment D) as a Function of Temperature.

9310M: This experimental composition has lower manganese, silicon, chromium and nickel than AISI 9315 (see Table 4) in order to reduce the cost of the alloy. As can be seen by comparing the fracture toughness results for 9315 with 9310M (see Table 9 and Figure 28), no significant difference in toughness is seen at temperatures up to 300°C. The main limitation of 9310M in comparison to 9315 or 4820 is its lower hardness. The room temperature hardness (Table 8) of 9310M is over 8 R_c points lower than 9315 or 4820, which means that it has a lower yield strength and lower hot hardness than either of these steels.

EX55: This steel is being used extensively by Hughes Tool Company in large diameter bits where high hardenability is important. The fracture toughness of EX55, listed in Table 9 and illustrated in Figure 29, drops slightly between room temperature and 100°C, above which temperature toughness remains essentially constant. The toughness of EX55 is much lower at room

Figure 29. Fracture Toughness of EX55 (Heat Treatment E) as a Function of Temperature.

temperature than any of the other conventional drill bit steels in the program. At 300°C, the toughness of EX55 is comparable to 4820 or 8620, but 9315 is significantly tougher. The low room temperature toughness of EX55 suggests that steels with fracture toughness values as low as 70 MPa√m will not fail by breakage during normal rock drilling conditions. It should be noted, however, that the hot hardness of EX55 is comparable to the other conventional drill bit steels and therefore will not allow penetration rates under geothermal conditions comparable to those experienced during typical rock drilling. These results indicate, however, that a steel with a case hardness above approximately R_c 57 (core hardness above R_c 40) and a fracture toughness greater than 70 MPa√m above 200°C will permit penetration rates during geothermal conditions comparable to those experienced during conventional rock drilling.

CBS 600: The temperature-dependent fracture toughness of CBS 600 steels is illustrated in Figure 30 and listed in Table 10. The 835°C (1535°F)

Figure 30. Effect of Temperature on the toughness of CBS 600.

Table 10
Fracture Toughness of Timken CBS Steels

Steel Type	Specimen Diameter (mm)	Heat Treatment Code*	Test Temperature (°C)	K _{IcSR} (MPa√m)			
				Individual Values	Mean	Standard Deviation	Coefficient of Variation
CBS 600-#1	50.8	F	22	152.8, 155.3	154.1	1.8	1.2
CBS 600-#1	50.8	H	22 300	109.1, 112.0, 113.3 86.9, 86.9	111.5 86.9	2.2 0.0	1.9 0.0
CBS 600-#2	25.4	F	22	104.7, 102.2	103.5	1.8	1.7
			100	85.9, 85.1	85.5	0.57	0.66
			200	59.7, 63.3	61.5	2.6	4.1
			300	57.9, 59.5	58.7	1.1	1.9
			400	72.4, 71.1	71.8	0.92	1.3
CBS 600M-#1	25.4	G	22	72.5, 69.5, 66.2	69.4	3.2	4.5
CBS 600M-#2	25.4	G	22	71.5, 70.6, 66.7	69.6	2.6	3.7
CBS 1000M-#1	50.8	I	22	56.4, 57.6	57.0	0.85	1.5
			300	79.5	79.5	--	--
CBS 1000M-#1	50.8	J	22	48.2, 41.8	45.0	4.5	10.0
			100	46.0, 51.2	48.6	3.6	7.5
			300	56.2	56.2	--	--
CBS 1000M-#2	25.4	K	22	71.1, 71.0	71.0	0.08	0.11
			100	131.0, 120.6	125.8	7.4	5.9
			200	102.6, 108.7	105.7	4.3	4.0
			300	100.7, 103.3	102.0	1.9	1.8
			400	106.7, 107.8	107.3	0.78	0.73
CBS 1000M-#2	25.4	L	22	73.7, 70.0	71.8	2.6	3.7
			100	118.0, 108.9	113.5	6.5	5.7
			200	99.7, 103.0	101.3	2.3	2.3
			300	93.2, 89.1	91.1	2.9	3.2
CBS 1000M-#2	25.4	M	22	62.4, 62.5	62.4	0.08	0.12
			100	132.1, 129.5	130.8	1.84	1.4
			200	131.1, 125.3	128.2	4.1	3.2
			300	107.8, 108.4	108.1	0.39	0.36
CBS 1000M-#3	25.4	N	22	79.0, 76.5	77.7	1.7	2.2
			100	65.4, 66.1	65.8	0.44	0.67
			200	65.8	65.8	--	--
			300	56.6, 59.7	58.1	3.8	2.2
			400	62.6, 57.2	59.9	3.8	6.4
CBS 1000M-#3	25.4	O	22	67.0, 72.7	69.9	4.1	5.8
			100	69.3, 73.4	71.3	2.9	4.1
			200	59.5, 58.4	58.9	0.73	1.2
			300	52.6, 46.7	49.6	4.2	8.4
CBS 1000M-#4	25.4	N	22	71.7, 82.6	77.1	7.7	10.0
			100	63.4, 70.8	67.1	5.2	7.8
			200	66.3, 64.3	65.3	1.4	2.1
			300	66.0, 58.5	62.3	5.3	8.5
			400	59.4	59.4	--	--
CBS 1000M-#4	25.4	O	22	75.0, 72.5	73.7	1.7	2.4
			100	67.3, 66.7	67.0	0.48	0.72
			200	60.6, 60.5	60.6	0.02	0.04
			300	57.3, 56.5	56.9	0.61	1.1
			400	56.0	56.0	--	--

*See heat treatment code in Appendix A for explanation.

hardening temperature (heat treatment F) of the CBS 600-#1 specimens produced the highest toughness ($154.1 \text{ MPa}\sqrt{\text{m}}$) in room temperature tests. The microstructure had considerable ferrite mixed with the martensite. When the same heat treatment was applied to 25.4 mm diameter CBS 600-#2 specimens, 40% acicular ferrite was observed (Figure 22A). The 25.4 mm CBS 600-#2 specimens were significantly less tough at room temperature than were the 50.8 mm CBS 600-#1 specimens (Table 10) probably due to the lower ferrite content in CBS 600-#2, as indicated by an increase in hardness over CBS 600-#1 (Table 8). The toughness of the 25.4 mm specimen dropped sharply from 103.5 to $61.5 \text{ MPa}\sqrt{\text{m}}$ between room temperature and 200°C .

The 870°C (1600°F) hardening temperature (heat treatment H) produced an entirely martensitic microstructure (Figure 22B) with about the same austenite grain size as the 835°C austenitizing temperature. It is interesting to note that specimens having a 100% tempered martensite microstructure had a lower toughness at room temperature ($111.4 \text{ MPa}\sqrt{\text{m}}$) than the ferrite-martensite cylinders of the same size. The room temperature hardness was $44.6 R_C$ for the martensitic structure and $38.4 R_C$ for the martensite-ferrite, indicating a trade-off in hardness and toughness. CBS 600-#2 hardened at 870°C had a toughness of $86.9 \text{ MPa}\sqrt{\text{m}}$ at 300°C , perhaps indicating that a totally martensitic structure may retain toughness better with increasing temperature than microstructures containing ferrite.

The composition of CBS 600 steel was modified by the addition of nickel (Table 4). CBS 600M-#2 contained approximately 1.5% nickel and CBS 600M-#1 approximately 2.0% nickel which would be expected to increase the toughness in comparison to CBS 600. As can be seen in Figure 30, the room temperature toughness of both CBS 600M-#1 and CBS 600M-#2 is lower than the toughness of CBS 600 steels. The lower toughness is probably due to the higher purity of

the vacuum melted CBS 600 materials as compared to the air melted CBS 600M steels. It is well known that sulfur content and sulfide shape affect the notch toughness of steels[23] and recent work has shown that reduction of sulfur content can improve greatly the fracture toughness of alloy steels (Figure 31)[24]. It is likely that higher sulfur content is lowering the toughness of the CBS 600M steels. The totally martensitic structure of the CBS 600M steels (Figure 22C) and high hardness (Table 8) also helps explain the lower toughness when compared to CBS 600-#1 steels heat treated at 835°C (heat treatment F). The fact that both CBS 600M steels had nearly the same toughness probably results from their identical hardness (Table 8) and similar compositions (Table 4).

CBS 1000M: Several heat treatments (see Appendix A) were used in determining the effect of austenitizing temperature on K_{IC} for CBS 1000M steels. All specimens had microstructures of tempered martensite with undissolved M_6C carbides. Figure 32 shows that CBS 1000M-#1, which was hardened at 955°C (open hexagon-shaped symbol) had a higher toughness than the same steel hardened at 1090°C (open triangles). This is due to the difference in grain size produced by the different hardening temperatures. The CBS 1000M-#2 cylinders austenitized at 955°C (heat treatment K, open square symbols) after a simpler heat treatment than CBS 1000M-#1 (heat treatment I, hexagons) had a higher hardness (R_c 39.8 versus R_c 38.2) as well as increased toughness (80.0 $MPa\sqrt{m}$ versus 57.1 $MPa\sqrt{m}$). It is important to realize, therefore, that hardness is not always sacrificed when improved toughness is obtained.

The most intriguing result of the CBS 1000M-#2 tests was the large increase in toughness between room temperature and 100°C. This increase in toughness correlates well with the brittle-to-ductile fracture transition of this steel as seen in micrographs B9-B11 (Appendix B).

Figure 31. Fracture Toughness of SAE 4340 Steel Hardened to R_c 40 (Electroslag casting is coded ESC).

Figure 32. Temperature Dependence of Toughness for CBS 1000M.

The compositions of CBS 1000M-#1 and CBS 1000M-#2 were very similar, but substantial modifications were made in the compositions of CBS 1000M-#3 and CBS 1000M-#4 (see Table 4) which significantly lowered the cost of these steels. The lower carbon content of these steels, as compared to CBS 1000M-#1 and CBS 1000M-#2, should increase the toughness while lower nickel and molybdenum may decrease toughness and hardenability. It is surprising to observe that austenitizing temperature and alloy content, within the ranges investigated, have very little effect on toughness since CBS 1000M-#3 and CBS 1000M-#4 have the same toughness behavior for both hardening temperatures (see solid symbols, Figure 32).

The CBS 1000M-#3 or CBS 1000M-#4 steels did not increase in toughness between room temperature and 100°C. This is consistent with a shift in the ductile to brittle transition temperature to lower temperatures as the carbon content decreases. The slight decrease in toughness between room temperature

and 200°C, therefore, probably corresponds to the similar decrease in toughness between 100°C and 300°C for CBS 1000M-#2 steels. It is also likely that the reason the toughness of CBS-1000M-#3 and CBS 1000M-#4 is lower than that of CBS 1000M-#2 is due to changes in the melt practice from air induction melted to VIMVAR respectively (see Table 4). The sulfur content is approximately 0.023% for CBS 1000M-#3 and CBS 1000M-#4 and only 0.007% for the vacuum arc remelted CBS 1000M-#2 steels. The higher sulfur content is probably responsible for the decreased toughness[23,24]. A thorough study of the effect of sulfur content and sulfide shape on fracture toughness (K_{IC}) of drill bit steels should be conducted.

All CBS 1000M specimens had excellent toughness retention over the entire temperature range. The toughness data at 22°C for all CBS 1000M steels hardened below 1090°C were comparable to those of EX55, but substantially lower than 4820, 8620 and 9315. It is likely that higher toughness over the entire temperature range tested can be obtained by vacuum arc remelting CBS 1000M-#3 or CBS 1000M-#4. As can be seen from Figure 10, CBS 1000M has the best wear resistance of any steel in the test program. However, the high cost of CBS 1000M steels, even at the lower nickel and molybdenum levels, militate against their widespread use.

EX-00053: The fracture toughness data for EX-00053 are listed in Table 11. Even using 50.8 mm diameter specimens and employing the short rod technique, the toughness is difficult to measure because of the large plastic zone in the test cylinders at elevated temperatures. In certain temperature ranges the tests were invalid because of excessive plasticity. Estimated values, K_Q , for K_{IC} were calculated for some cases where invalid results were obtained by following the empirical relationship[19]:

$$P = 0.075 \left[\frac{B}{(K_{IC}/\sigma_{y.s.})} \right]^{-1.6} \quad (1)$$

Table 11

Short Rod Fracture Toughness of Carpenter EX-00053

Steel Type	Specimen Diameter (mm)	Heat Treatment Code*	Test Temperature (°C)	K_{IcSR} (MPa√m)			
				Individual Values	Mean	Standard Deviation	Coefficient of Variation
EX-00053-#1	50.8	P	22	97.8, 109.4	103.6	8.3	8.0
			100	264.6, 292.1†	264.6	--	--
			200	219.7, 222.9	221.3	2.3	1.0
			300	170.7, 165.7	168.2	3.6	2.1
			400	203.7†	203.7†	--	--
EX-00053-#2	50.8	P	22	109.3, 81.7	95.5	19.5	20.4
			50	92.6, 86.3	89.5	4.5	5.0
			75	126.2	126.2	--	--
			265	289.1	289.1	--	--
			300	263.9	263.9	--	--
EX-00053-#2	50.8	P-2	22	126.2	126.2	--	--
			30	176.2	176.2	--	--
EX-00053-#2	50.8	Q	22	76.2, 100.1, 77.3, 76.4	82.5	11.8	14.3
			30	97.5	97.5	--	--
			40	88.4	88.4	--	--
			60	167.0	167.0	--	--
			80	375.2††	375.2††	--	--
			100	378.5††, 375.2††	376.9††	2.3†	0.62†
			200	322.2†	322.2†	--	--
			300	212.1†	212.1†	--	--
			400	249.5†	249.5†	--	--
			450	239.6†	239.6†	--	--
EX-00053-#1	19.1	P	-100	42.4, 40.2	41.3	1.6	3.8
			-90	39.2, 48.3	43.8	6.4	14.7
			-85	42.1, 43.2	42.7	0.82	1.9
			-70	50.1	50.1	--	--
			-50	53.9	53.9	--	--
			-30	56.3	56.3	--	--
			-10	63.8	63.8	--	--
			10	86.8, 87.6	87.1	0.69	0.79
			22	96.9, 96.2	96.5	0.53	0.55
			30	120.2, 120.6	120.4	0.29	0.24
			40	130.2, 124.7, 119.6	124.8	5.29	4.2
			45	125.9	125.9	--	--

*See heat treatment code in Appendix A for explanation.

† K_Q - Fracture toughness estimate. K_{Ic} invalid due to excessive plasticity in test specimen.†† K_Q estimate is very rough due to p value greater than 0.50.

where P is the plasticity factor as determined in the short rod test[9], B is the specimen diameter, K_{IC} is the fracture toughness and $\sigma_{y.s.}$ is the yield strength of the material. When P values are less than 0.20, then valid fracture toughness results are obtained. At P values between 0.20 and 0.50, K_Q replaces K_{IC} and can be used to estimate K_{IC} . There are not enough data for a good estimate of K_{IC} for P values above 0.50.

Valid fracture toughness data are shown in Figure 33. Data for EX-00053-#1 (heat treatment P) indicate that the room temperature toughness ($103.6 \text{ MPa}\sqrt{\text{m}}$) is comparable to conventional steels (except EX55). The toughness increases sharply at 100°C ($265 \text{ MPa}\sqrt{\text{m}}$) and the steel becomes even more ductile with increasing temperature (Figures B13 and B14, Appendix B).

Attempts to duplicate the toughness between room temperature and 400°C have not been entirely successful. Two heats of steel and slight variations in heat treatments produced considerable scatter in the room temperature data

Figure 33. Effect of Test Temperature on Fracture Toughness of EX-00053.

(individual values ranged between 76.2 MPa $\sqrt{m}$ and 126.2 MPa $\sqrt{m}$). The scatter appears to be due to differences in heat treatment and to slightly different yield strengths (Table 11) which affected the plastic zone size in the specimens. Despite this scatter in the data, the toughness always increased dramatically between room temperature and 100°C. The fracture toughness of EX-00053-#2 (heat treatment P) was at least 220 MPa $\sqrt{m}$ at temperatures between 100°C and 250°C, based on the relationship[9]:

$$B > 1.0 \left[\frac{K_{Ic}}{\sigma_{y.s.}} \right]^2 \quad (2)$$

where the parameters are as defined before. This empirical relationship also indicates that the toughness must be greater than 220 MPa $\sqrt{m}$ for EX-00053-#2 (heat treatment P-2) above 50°C and for EX-00053-#1 (treatment Q) above 60°C.

The mechanism of fracture in EX-00053 is crack jump[9] at temperatures below 50-70°C and smooth crack growth above that temperature range. In order to verify that the steel becomes less ductile as temperature decreases, 19.1 mm diameter cylinders were tested at temperatures between -100°C and 45°C. As can be seen in Figure 33 (EX-00053-#1, 19.1 mm, heat treatment P, triangular symbols) there is little scatter in the data below room temperature and an increase in toughness with increasing temperature, greatly accelerated above -10°C, is observed.

It is interesting to compare the toughness of CBS 1000M-#4 (heat treatment O) with the EX-00053 steels since the heat treatments are nearly identical and the chemical compositions are similar (Table 4) except that EX-00053 steels have lower sulfur and approximately 2% copper. As discussed before, sulfur lowers the toughness, but it is doubtful that the toughness of CBS 1000M-#4 would be above 140 MPa $\sqrt{m}$, the maximum toughness measured on VIMVAR CBS 1000M. The high toughness of EX-00053 (greater than 240 MPa $\sqrt{m}$ in this

same range) appears to be due to copper, which precipitates in the tempered martensite matrix. Further studies are needed to establish the reasons for the high toughness of EX-00053.

The EX-00053 steel is an excellent candidate for applications requiring exceptional toughness at elevated temperatures. The toughness of EX-00053 is higher than the conventional drill bit steels over the entire temperature range. The carbon content of EX-00053 could be raised if increased yield strength and decreased toughness was desired. The properties of air induction melted EX-00053 should be investigated since this steel would be more cost competitive with 9315. The high molybdenum content of EX-00053, however, is the main reason for the high cost. Carbide formers such as molybdenum and chromium are, of course, essential in applications where high hot hardness is required.

Vasco X-2M: Fracture toughness data for the X-2M steels are listed in Table 12 and illustrated in Figure 34. Heat treatments S-Z were done at Teledyne/Vasco while heat treatment R was done independently. Comparison of microstructures (see Figures 25B, 25C and 25D) and hardness (Table 9) indicate that the maximum temperature reached during heat treatment R was probably 1065°C rather than the specified 1120°C. None of the heat treatments produced an entirely martensitic microstructure. The microstructures were mixtures of tempered martensite and ferrite. The amount of primary ferrite decreased as the austenitizing temperature and carbon content increased (see Figures 25B-25J), in agreement with Fopiano, et al[21].

After austenitizing at high temperatures, the toughness of X-2M is almost independent of temperature as illustrated by X-2M-#1, heat treatment R (solid circles in Figure 34). An excellent correlation between crack behavior on the test record (Table 7) and appearance of the fracture surface was noted. The

Table 12

Short Rod Fracture Toughness of Vasco X-2M

Steel Type	Specimen Diameter (mm)	Heat Treatment Code*	Test Temperature (°C)	K_{ICSR} (MPa√m)		
				Individual Values	Mean	Coefficient of Variation
Vasco X-2M-#1	50.8	R	22	46.4, 49.7	48.1	4.9
			100	62.8, 64.0	63.5	1.3
			200	65.7, 67.8	66.8	2.2
			300	65.6, 61.4	63.5	4.7
			400	61.6, 59.3	60.5	2.7
		S	300	107.9, 107.7, 88.6	101.4	10.9
		T	300	69.6, 73.5, 78.4	73.8	6.0
		U	300	55.3, 63.1, 55.3	57.9	7.7
		UU	300	92.7, 125.6†, 109.9†	92.7	--
		V	300	94.9, 93.3, 88.8	92.3	3.4
Vasco X-2M-#2	25.4	W	22	67.8, 68.4, 64.3	66.8	3.3
			100	117.4, 120.0	118.7	1.8
			200	104.5, 94.4	99.5	7.2
			300	71.9, 72.4, 78.0	74.1	4.6
			400	86.9	86.9	--
			450	76.3	76.3	--
		X	22	75.6, 81.2, 82.9	79.9	4.8
			100	169.2†	169.2†	--
			200	159.2†, 152.5	152.5	--
			300	108.8, 100.5, 105.7	105.0	4.0
			400	99.5, 104.1	101.8	3.2
		Y	22	98.3, 96.5, 103.7, 102.9, 111.1	102.5	5.6
		Z	22	122.0, 111.9, 104.7, 114.6	113.3	6.3

*See Appendix A for explanation of heat treatment code.

† K_Q - Fracture toughness estimate. K_{IC} invalid due to excessive plasticity in the test specimen.

Figure 34. Effect of Test Temperature on the Toughness of X-2M.

SEM micrographs (Figures B15-B18) show a change from brittle cleavage to ductile fracture at test temperatures between 100°C and 200°C. This appeared on test records as a change from crack-jump behavior to smooth crack growth. Surprisingly, there was no corresponding increase in toughness between 100°C and 200°C.

As the austenitizing temperature was decreased, the toughness became very temperature dependent. A dramatic increase in toughness occurred between room temperature and 100°C for X-2M-#2 steels after austenitizing at 980°C (1800°F) and 955°C (1750°F) (solid squares and diamonds in Figure 34). The toughness of Vasco X-2M-#1 (heat treatment R) may be sensitive to temperature and show an increase in toughness with increasing temperature, similar to X-2M-#2 steels, if the test range is extended to lower temperatures. The lower carbon content of X-2M-#1 should shift the ductile-to-brittle transition temperature to below that for X-2M-#2. K_{IC} measurements below room temperature are needed to verify this hypothesis.

The fracture toughness at 22°C increased as the austenitizing temperature was increased from 900°C (1600°F) to 980°C (1800°F) as illustrated by Vasco X-2M-#2 steels in Figure 34. Hardening temperatures of 900°C and 925°C (heat treatments Z and Y) produced microstructures containing approximately 50% and 40% ferrite respectively. The toughness of these steels could not be measured above room temperature ($K_{IC} > 125 \text{ MPa}\sqrt{\text{m}}$) because of the large plastic zone size in the 25.4 mm cylinders, and 50.8 mm specimens are required to obtain valid K_{IC} data. It should be realized, however, that the increased toughness with decreasing hardening temperature is accompanied by a decrease in hardness and yield strength (Table 9). The hardness at 315°C for X-2M-#2 is shown in Table 13. It is doubtful that austenitizing temperatures below 980°C would produce sufficient hot hardness for high-temperature use.

Table 13
Hot Hardness of Vasco X-2M[25]

Steel Type	Heat Treatment Code*	Austenitizing Temperature (°C)	Rockwell C Hardness at 315°C
X-2M-#2	W	980	44.6
X-2M-#2	X	955	35.1
X-2M-#2	Y	925	27.5
X-2M-#2	Z	900	23.7

*See Appendix A for explanation of heat treating code.

The effect of ferrite content and grain size on toughness is shown in Figure 35. The toughness increases at both very low ferrite contents (high hardening temperatures) and high ferrite contents (low austenitizing temperatures) with a minimum near 25% ferrite (1010°C austenitizing temperature). At hardening temperatures above 1010°C, the increase in toughness is accompanied by an increase in hardness, whereas below 1010°C, the increased toughness is obtained at the expense of hardness (Tables 9 and 12).

Figure 35. Effect of Austenitizing Temperature on the Toughness of X-2M.

Although the toughness of all X-2M steels tested was equal to or better than the toughness of conventional steels above 100°C, the requirement for high toughness ($K_{IC} > 70 \text{ MPa}\sqrt{\text{m}}$) at ambient temperature (bits must be able to withstand impact during fabrication, shipping and drilling at non-geothermal temperatures) and high hardness at elevated temperatures limit the acceptable austenitizing temperatures for X-2M to 1120°C, and possibly 1065°C and 988-955°C. High austenitizing temperatures (1120°C and 1065°C) call for furnace equipment not generally used by bit manufacturers. Although the 955°C hardening temperature is within reach of conventional heat treating furnaces, reproducing of hardness and yield strength would be difficult on a commercial basis.

Fracture Toughness Summary

The toughness of the steels tested is compared in Figure 36. It is apparent that EX-00053 has superior toughness at elevated temperatures and

Figure 36. Toughness Comparison of Conventional and High Wear Resistant Steels.

that CBS 1000M is the only steel which consistently has K_{IC} values equal or superior to 9315 between 100°C and 300°C. The other obvious trend is that steels with tempered martensite structures (9315, EX55, CBS 1000M, EX-00053) have much better toughness retention over the temperature range investigated than steels containing ferrite or bainite (4820, 8620, CBS 600-#2 (heat treatment F), X-2M-#2 (heat treatment W)). These latter steels drop rapidly in toughness with increasing temperature.

The ductility transition that occurs between room temperature and 200°C for EX-00053, CBS 1000M and X-2M steels appears to depend upon carbon content (Figures 32 and 34) and possibly on austenitizing conditions (Figures 32 and 33). The transition shifts to higher temperatures with increasing carbon content.

If EX55 is assumed to be a steel capable of resisting impact failure during conventional rock drilling, then the fracture toughness of any candidate steel to be used in geothermal drilling applications should have fracture

toughness at elevated temperatures equal to or greater than the toughness of EX55 between 22 and 100°C. On this criterion, all EX-00053 steels, CBS 1000M steels (austenitized below 1090°C), 9315 and 9310M, 8620, and X-2M (austenitized at 1120°C or below 980°C) have acceptable toughness. To be capable of conventional rock drilling penetration rates during geothermal drilling the candidate steels must have high case and core hardness to provide the necessary yield strength and wear resistance. A steel with a case hardness of R_C 55 or greater at 300°C (Figure 10) and a core yield strength greater than 900 MPa (Table 8) should provide the necessary strength and wear resistance to allow conventional penetration rates during geothermal drilling. When these criteria are coupled with the toughness requirement, only EX-00053, CBS 1000M (austenitized below 1090°C) and X-2M (austenitized at 1120°C or 980°C) appear to be acceptable. Vasco X-2M has heat treating limitations as discussed above and both EX-00053 and CBS 1000M are expensive. The ability of these steels to resist impact fracture during use as stabilizers and bits in geothermal drilling would allow penetration rates comparable to conventional rock drilling to occur in geothermal wells. The savings resulting from the increased penetration rate should offset the greater cost of the bit[2].

Fatigue Crack Resistance Measurements

Extensive data on fatigue crack growth behavior in metallic systems have been generated[26]. These studies have proven the validity of the Paris power law in the region where stable crack growth occurs[18]. The approach is useful because a knowledge of fracture toughness and fatigue properties allows an estimate to be made of the maximum allowable initial flaw size if the operating stress level is known. Alternatively, it is possible to estimate a maximum allowable stress for a given flaw which will not allow it to grow to critical dimensions during the intended life of the component[18]. Although

fatigue data are not presently used to predict bit failure, it was believed that wear-resistant steels should have fatigue behavior at high temperatures at least equal to that of conventional bit steels at room temperature. This may be an over-simplification since conventional rock bits do operate at elevated temperatures.

It was expected that m values from the Paris power law ($da/dn = C(\Delta K)^m$) would be in the range of two to four for all steels tested and that the slopes would simply be shifted to higher or lower ΔK value for a given crack propagation rate. The test results, however, did not meet these expectations, as can be seen in Table 14 and in Figures 37 through 48. A brief discussion of the individual test results follows.

AISI 4820: Although no data were found in the literature for crack propagation rates in 4820, the results shown in Figure 37 indicating an m value of 3.05, are reasonable. The line indicating the fit of the data is extended beyond the actual data points. The curve will bend down at low propagation

Figure 37. Crack Growth Rate as a Function of Stress Intensity Factor for AISI 4820.

Table 14
Fatigue Crack Resistance

Steel Type	Heat Treatment Code*	Test Temperature (°C)	Frequency (Hz)	Test	K _{max} (MPa√m)	C†	M†	r ² **	Results Displayed in Figure
4820	A	22	5	1	62.6	1.16x10 ⁻⁵	3.14	0.92	37
				2	60.8	1.65x10 ⁻⁵	2.98	0.98	
				1,2	62.6	1.36x10 ⁻⁵	3.05	0.96	
8620	B	22	5	1	70.1	4.67x10 ⁻²¹	13.83	0.97	33
				2	80.7	2.21x10 ⁻²¹	13.43	0.92	
				1,2	80.7	6.59x10 ⁻¹⁸	11.38	0.75	
9315	C	22	5	1	73.4	3.44x10 ⁻³	1.46	0.57	39
			5	2	78.4	2.44x10 ⁻⁴	2.16	0.89	
			5	1,2	78.4	4.78x10 ⁻⁴	1.97	0.82	
			10	3	83.1	3.33x10 ⁻⁴	1.89	0.99	
CBS 600-#1	F	300	5	1	65.4	6.26x10 ⁻¹³	7.99	0.62	40
				2	51.1	5.87x10 ⁻⁷	4.29	1.00	
				1,2	65.4	4.72x10 ⁻⁸	4.92	0.40	
CBS 600-#2	F	22	10	1	65.4	2.38x10 ⁻⁶	3.24	0.86	40
				2	51.1	1.74x10 ⁻²	0.75	0.88	
				1,2	65.4	1.51x10 ⁻⁶	3.31	0.81	
CBS 1000M-#1	I	300	5	1	49.7	2.20x10 ⁻¹²	8.24	0.96	41
				2	64.0	1.18x10 ⁻⁵	3.19	0.95	
				1,2	64.0	3.41x10 ⁻⁴	2.36	0.40	
CBS 1000M-#2	K	22	10	1	54.2	8.83x10 ⁻¹⁰	3.34	0.78	41
				2	61.6	1.32x10 ⁻⁶	1.49	0.61	
				3	70.1	2.16x10 ⁻³	-2.13	1.00	
				1-3	70.1	1.19x10 ⁻⁶	3.29	0.82	
EX-00053-#1	P	300	5	1	94.8	3.02x10 ⁻¹²	6.64	0.96	42
				2	70.8	7.12x10 ⁻²	1.01	0.11	
				1,2	94.8	1.87x10 ⁻⁸	4.68	0.59	
Vasco X-2M-#1	R	300	5	1	46.5	5.03x10 ⁻⁹	5.74	0.89	43, 48
				2	52.1	7.74x10 ⁻¹⁰	6.40	0.98	
				1,2	52.1	2.13x10 ⁻⁹	6.04	0.93	
Vasco X-2M-#2	Z	300	10	1	85.5	2.70x10 ⁻⁴	1.94	0.95	44, 48
				2	89.7	4.98x10 ⁻⁴	2.35	0.94	
				1,2	89.7	1.59x10 ⁻⁴	2.07	0.93	
		22	10	3	105.6	2.59x10 ⁻⁴	1.94	0.97	
				4	89.5	8.55x10 ⁻³	1.13	1.00	
				5	95.0	8.43x10 ⁻⁴	1.71	0.97	
Vasco X-2M-#2	Y	300	10	3-5	105.6	7.64x10 ⁻⁴	1.71	0.91	45, 48
				1-5	105.6	3.06x10 ⁻⁴	1.93	0.91	
		22	10	1	89.3	6.31x10 ⁻⁶	2.95	1.00	
				2	60.7	5.19x10 ⁻⁶	3.03	1.00	
				3	70.1	1.43x10 ⁻⁵	2.64	1.00	
				1-3	89.3	6.26x10 ⁻⁶	2.94	0.96	
Vasco X-2M-#2	X	300	10	4	76.1	1.43x10 ⁻⁴	2.12	0.98	46, 48
				5	74.4	1.21x10 ⁻⁴	2.22	0.99	
				4,5	76.1	1.38x10 ⁻⁷	2.15	0.97	
		22	10	1-5	89.3	4.25x10 ⁻⁶	2.45	0.92	
				1	74.0	2.35x10 ⁻³	1.24	1.00	
				2	63.4	2.54x10 ⁻¹	0.15	1.00	
Vasco X-2M-#2	W	300	10	3	58.6	2.48x10 ⁻⁴	2.68	1.00	47, 48
				2,3	63.4	2.84x10 ⁻⁴	1.99	0.78	
				1-3	74.0	1.90x10 ⁻³	1.39	0.45	
		22	10	1	56.8	6.47x10 ⁻¹¹	5.25	1.00	
				2	48.6	2.95x10 ⁻⁴	1.73	1.00	
				3	55.7	---	---	---	
Vasco X-2M-#2	W	22	10	2,3	55.7	9.09x10 ⁻⁴	1.69	1.00	47, 48
				1-3	56.8	5.15x10 ⁻⁴	1.85	0.93	

*See Appendix A for explanation of heat treating code.

†Constants as defined in Equation (2) where ΔK is in MPa√m and (da/dn) √1-R is in μm/cycle.

**Correlation coefficient squared.

rates and curve up at higher rates because of crack initiation and unstable crack growth, respectively. It is generally believed that the region between 0.1 and 10 $\mu\text{m}/\text{cycle}$ is well within the stable region (often referred to as Region II) of crack growth. AISI 4820 showed little crack closure and as stated earlier, crack closure was avoided for all tests since cracks do not propagate when the crack has closed.

AISI 8620: An exceptionally high m value (11.38) was calculated from the test data and individual tests indicated an even higher m value of approximately 13.6. The first test was conducted with a specimen which was slotted before heat treating while the second test used a cylinder which had been heat treated and then slotted. The similar results for both tests, as shown in Figure 38, indicate that residual stresses and microstructure were not the main reason for the anomalously high m value. The 8620 steel, however, displayed significant crack closure, such that a $K_{\min}$ of 50 $\text{MPa}\sqrt{\text{m}}$ and 62 $\text{MPa}\sqrt{\text{m}}$ were used for the two tests. The maximum stress intensity, 80.7 $\text{MPa}\sqrt{\text{m}}$,

Figure 38. Crack Growth Rate as a Function of Stress Intensity Factor for AISI 8620.

used in the second test approaches 70 percent of K_{Ic} . Although many investigators have produced evidence of accelerating rates of fatigue crack growth approaching final fracture, the separate contributions of ΔK and K_{max} have not been carefully examined[27]. It appears that both ΔK and K_{max} contribute towards the accelerating rates of crack propagation as the conditions for failure are approached. The high values of K_{min} and K_{max} required to reach the 20-40 $MPa\sqrt{m}$ ΔK range, due to crack closure, were apparently the cause of the steep slope of the log-log plot. It should be stressed that crack closure is not a peculiarity of the short-rod technique but is caused by plastic deformation or residual stresses within the specimens. The anomalous behavior is not entirely explained by crack closure constraints since high K_{max}/K_{Ic} ratios would normally cause crack growth rates above 10 $\mu m/cycle$ if catastrophic failure were occurring[25]. No data were found in the literature for AISI 8620.

AISI 9315: 9315 was the only steel tested for which previous data were obtained from the literature. Crack initiation occurred between 4 to 6 $MPa\sqrt{m}$ and the cyclic stress intensity factor for a 0.01 $\mu m/cycle$ crack propagation rate was 10 $MPa\sqrt{m}$ [28]. Figure 39 agrees quite well with these data since an extrapolation of the observed data for 9315 gives a ΔK of 5 $MPa\sqrt{m}$ at 0.01 $\mu m/cycle$. An m value near 2 is also consistent with what would be expected at room temperature for this steel[18].

Tests 1 and 2 (solid black line in Figure 39) were conducted at 5 Hz while test 3 data (dashed line) were taken at 10 Hz. Slightly different compliance calibrations and data recording techniques were used in test 3 than in tests 1 and 2 (see Experimental Procedure section). The results from the three tests are nearly identical, indicating that AISI 9315 is fairly insensitive to frequency between 5 and 10 Hz.

Figure 39. Crack Growth Rate as a Function of Stress Intensity Factor for AISI 9315.

CBS 600: CBS 600 was tested at 300°C, as were CBS 1000M, EX-00053 and X-2M. Although it is widely known that temperature often affects crack propagation rates[18], it is not clear whether temperature changes the m values or the crack propagation rate[27]. The tests of CBS 600-#1 (heat treatment F) show a high degree of scatter in the data (see Figure 40) and the m value of 4.9 is therefore somewhat arbitrary. The 50.8 mm diameter cylinders tested in fatigue were from the same heat treatment that produced the 154 MPa√m room temperature static fracture toughness value. Although there were not enough 50.8 mm cylinders to test the static toughness at 300°C it is apparent that it drops rapidly, as evidenced by the 25.4 mm data and that the 65.4 MPa√m K_{max} value is approaching K_{IC} for the material. Crack closure was not a major problem with the lack of data at low crack growth rates. Longer tests at ΔK values near 20 MPa√m would help to clarify the fatigue behavior of this steel.

Figure 40. Crack Growth Rate as a Function of Stress Intensity Factor for CBS 600.

The fatigue crack resistance of 25.4 mm diameter CBS 600-#2 (heat treatment F) short rod specimens was measured at room temperature to determine the effect of temperature on crack growth in this steel. There were no significant differences in crack growth rate between 22°C and 300°C, as illustrated in Figure 40. It should be noted, however, that the test data are limited, frequencies differed between the two tests (Table 14) and the compositions (Table 4) and properties (Tables 8 and 10) of the two steels were not the same.

CBS 1000M: The two tests on CBS 1000M-#1 (heat treatment I) at 300°C gave different results, as shown in Figure 41. The m value of 3.2 for test 2 (square symbols) may be more valid than the combined value of 2.4. Both cylinders were austenitized at 955°C and the K_{IC} of 79.5 $MPa\sqrt{m}$ in the static test at 300°C was approached by the K_{max} of 70.4 during the second test. There was only minor crack closure observed in these specimens and extrapolation of

Figure 41. Crack Growth Rate as a Function of Stress Intensity Factor for CBS 1000M.

the data below a ΔK of $20 \text{ MPa}\sqrt{\text{m}}$ is not advisable since no crack growth was observed in this region.

Fatigue crack resistance at room temperature was measured at 10 Hz on 25.4 diameter CBS 1000M-#2 (heat treatment K) cylinders. The 22°C results (dashed line) are compared to the 300°C data (solid line) for CBS 1000M-#1 (heat treatment I) in Figure 41. An m value of 3.29, nearly identical to the 3.2 m value for test 2 at 300°C, was calculated based on the room temperature data. Based on the scatter in the test results, there were no apparent differences in fatigue crack growth rate between the two temperatures as was the case for CBS 600. It is important to note, however, that differences existed in the chemistry, toughness and hardness of the two CBS 1000M steels tested.

EX-00053: No test data could be obtained for EX-00053-#1 (heat treatment P) below a ΔK of $40 \text{ MPa}\sqrt{\text{m}}$, so the extrapolation of the line shown in Figure 42

Figure 42. Crack Growth Rate as a Function of Stress Intensity Factor for EX-00053-#1 (Heat Treatment P).

below a ΔK of $40 \text{ MPa}\sqrt{\text{m}}$ is arbitrary. The fact that all of the data from the second test are clustered around $10 \text{ }\mu\text{m/cycle}$ lowered the m value from the 6.6 observed in the first test to 4.7. More test data could be obtained at ΔK 's between 40 and $50 \text{ MPa}\sqrt{\text{m}}$ if longer tests were conducted. Crack closure was not a problem during these tests because of the high fracture toughness of EX-00053 at 300°C .

X-2M: Both tests on X-2M-#1 (heat treatment R) showed consistent results (Figure 43) with an m value of 6.0 for the combined tests. K_{max} values of 46.5 and $52.1 \text{ MPa}\sqrt{\text{m}}$ are about 75-80 percent of the K_{IC} ($63.5 \text{ MPa}\sqrt{\text{m}}$) observed during the static tests at 300°C . The data, however, are well within the region associated with stable crack growth.

Extensive testing of X-2M-#2 was performed at 22°C and 300°C on short rod specimens austenitized at 900°C (heat treatment Z), 925°C (Y), 955°C (X) and 980°C (W). All cylinders were cycled at 10 Hz during fatigue testing. The

Figure 43. Crack Growth Rate as a Function of Stress Intensity Factor for X-2M-#1 (Heat Treatment R).

Figure 44. Crack Growth Rate as a Function of Stress Intensity Factor for X-2M-#2 (Heat Treatment Z).

results of three 22°C tests and two 300°C tests for the 900°C hardening treatment are shown in Figure 44. Little scatter in the data was observed at both temperatures. An m value of 1.93 was calculated for room temperature tests, which was nearly identical to the 2.07 m value calculated from the 300°C data. The high toughness (Table 12) of the specimens austenitized at 900°C allowed higher ΔK 's and K_{max} (Table 14) than X-2M-#1 (heat treatment R). The m values for X-2M-#2 (heat treatment W) were significantly lower than those calculated for X-2M-#1 (heat treatment R).

The fatigue crack growth behavior of X-2M-#2 (heat treatment Y) at 22°C and 300°C is illustrated in Figure 45. An m value of 2.94 was calculated from the 300°C tests and 2.15 for those done at 22°C, with a combined m value of 2.45 for all tests. The experimental scatter was relatively small and K_{max} values were lower after this treatment than after heat treatment Z because of the lower toughness of the cylinders.

The fatigue data for short rod specimens hardened at 955°C (heat treatment X) and 980°C (heat treatment W) are shown in Figures 46 and 47 respectively. The experimental data are sparse for both heat treatments and not enough data are available to detect differences between the 22°C and 300°C test temperatures. The m values for the combined test data were respectively 1.39 and 1.85 for specimens austenitized at 955°C and 980°C.

When all of the fatigue data for Vasco X-2M are examined together (Figure 48), a number of observations can be made. The fatigue data for Vasco X-2M-#2 are relatively insensitive to austenitizing temperature and test temperature, for the test conditions employed since all of the data falls on the dashed line shown in Figure 48. The insensitivity to austenitizing temperature is surprising since wide differences in toughness resulted from the different heat treatments. The apparently different fatigue behavior of X-2M-#1 (heat

Figure 45. Crack Growth Rate as a Function of Stress Intensity Factor for X-2M-#2 (Heat Treatment Y).

Figure 46. Crack Growth Rate as a Function of Stress Intensity Factor for X-2M-#2 (heat treatment X).

Figure 47. Crack Growth Rate as a Function of Stress Intensity Factor for X-2M-#2 (Heat Treatment W).

Figure 48. Crack Growth Rate of Vasco X-2M Steels.

treatment R) as compared to X-2M-#2 is difficult to explain. It is possible that it is due to a sensitivity of the steel to cycling frequency, but none of the other steels tested have shown such a large sensitivity to frequency. It is more likely due to differences in the toughness of the specimens since Vasco X-2M-#1 (heat treatment R) is much lower in toughness than any of the X-2M-#2 steels (heat treatments X-Z) both at 22°C and 300°C (Table 12). The difficulty with this argument is that Vasco X-2M-#2 steels showed very little sensitivity to toughness over a wide range of K_{IC} values.

Combined Data: The data from all of the tests are displayed in Figure 49. Although the data points for 8620 span the entire length of the line, it must be emphasized that the other lines are extrapolations from the data at low and high ΔK values. As has been previously discussed, the data may not form a straight line in these regions, depending on where crack propagation begins and catastrophic failure starts.

Figure 49. Crack growth Rate as a Function of Stress Intensity Factor for all Steels Tested. (Note that 4820, 8620 and 9315 were tested at 22°C while CBS 600, CBS 1000M, EX-00053 and X-2M were tested at 300°C).

Obviously, the best way to evaluate the data is to pick the ΔK range associated with geothermal or conventional drilling. Unfortunately, the ΔK range to which the bits are presently subjected is not known. An alternative method of evaluation would be to pick a crack growth rate, below the critical rate for catastrophic failure, and observe the ΔK at which the rate occurs in an individual steel. The latter approach is a better method for comparing the steels in the test program since a crack growth rate can be picked within the experimental data of all of the steels.

If the steels in Figure 48 are compared at a growth rate $((da/dn) \sqrt{1-R})$ of $0.1 \mu\text{m}/\text{cycle}$, EX-00053 and 8620 would clearly have the highest ΔK ($30 \text{ MPa}\sqrt{\text{m}}$) while X-2M-#1 (heat treatment R), CBS 600 and 4820 would be intermediate ($20 \text{ MPa}\sqrt{\text{m}}$) and 9315 and CBS 1000M would display this growth rate at ΔK 's of approximately $15 \text{ MPa}\sqrt{\text{m}}$. X-2M-#2 (heat treatments X-Z) would be the least crack resistant with a ΔK of only $10 \text{ MPa}\sqrt{\text{m}}$. If, alternatively, the steels are compared at a growth rate of $1.0 \mu\text{m}/\text{cycle}$ then 9315, EX-00053 and 4820 display the highest ΔK 's ($40\text{--}50 \text{ MPa}\sqrt{\text{m}}$) while 8620, CBS 1000M and CBS 600 have this growth rate at a ΔK of $35 \text{ MPa}\sqrt{\text{m}}$, and X-2M-#1 (heat treatment R) at $30 \text{ MPa}\sqrt{\text{m}}$ and X-2M-#2 (heat treatments X-Z) at $20 \text{ MPa}\sqrt{\text{m}}$. The ΔK of interest is obviously critical since at a stress intensity level of $30 \text{ MPa}\sqrt{\text{m}}$, 8620 and EX-00053 have crack growth rates an order of magnitude slower than 9315 and CBS 1000M. At a ΔK of $50 \text{ MPa}\sqrt{\text{m}}$, however, the crack propagation rate in 9315, EX-00053 and 4820 is at least an order of magnitude slower than 8620 and X-2M.

The data generated suggest a wide variation in the room-temperature fatigue behavior of 4820, 8620 and 9315 which is not completely understood. The 300°C fatigue crack resistance data for the high wear resistant steels are certainly within the scatter of the conventional steels at room temperature. It appears that all of the steels, with the exception of Vasco X-2M-#2 (heat

treatments X-Z), would have adequate fatigue crack resistance when used at elevated temperature, based on the infrequent fatigue failures experienced by 4820, 8620 and 9315 in drill bits. Based on the limited testing performed, EX-00053 appears to show better fatigue crack resistance than CBS 600 and X-2M. It would also appear that EX-00053 is superior to CBS 1000M at ΔK 's less than $78-80 \text{ MPa}\sqrt{\text{m}}$. 8620 is clearly superior to 9315 and 4820 at ΔK 's up to $30 \text{ MPa}\sqrt{\text{m}}$ but 9315 and 4820 could only be used above $40 \text{ MPa}\sqrt{\text{m}}$ since cracks in 8620 grow catastrophically above this stress intensity.

SEM micrographs displayed in Figures B19 through B32 (see Appendix B) compare the fracture surfaces of fatigued samples to their statically tested counterparts at a corresponding temperature. There were no major differences between the mode of fracture in the static fracture toughness tests and the fatigue crack resistance tests. All samples appear to have failed in a ductile mode caused by microvoid coalescence. Striations are normally not observed in martensitic structures[25] and none were observed on the fractured surfaces of the fatigued samples. The dimples on static fracture surfaces were consistently larger than the voids on the fatigued surfaces, consistent with the much higher rate at which the fracture toughness measurements were made. The reason for the high m value for 8620, in contrast to normal m values for 4820 and 9315, was not explained by the SEM micrographs. Further fatigue testing is needed to clarify the behavior and to quantify differences between the steels.

Recommendations

EX-00053 has greater fracture toughness and fatigue crack resistance than other steels in the test program. CBS 1000M has adequate fracture toughness and fatigue crack resistance for geothermal drilling. CBS 1000M has a higher

case and core hot hardness than EX-00053 and may therefore be more wear resistant during geothermal drilling. The hardness and yield strength of EX-00053, however, could be increased at the expense of some loss in toughness by increasing the carbon content. The cost of CBS 1000M is higher than EX-00053 because of its greater molybdenum content. Vasco X-2M and CBS 600 have lower toughness and crack resistance than EX-00053 and CBS 1000M. Both steels may perform adequately, however, if heat treated so as to minimize the amount of primary ferrite in their microstructures.

The cost of the high temperature steels is compared to the price of conventional drill bit steels in Table 15. The greater cost of high temperature steels as compared to conventional steels is due to expensive alloying additions as well as more expensive melting practices. The reason why X-2M is more expensive than CBS 1000M and EX-00053 is not clear. Since no more than 60 kg of steel is consumed in the manufacturing of a 222 mm (8.75 in) diameter bit, the cost of the steel is less than 2% of the total cost of producing the bit. If the same bit were manufactured using EX-00053 instead of conventional alloys, and the price of the bit does not increase, the cost of the steel would account for approximately 13% of the cost of the bit. Since the machinability of EX-00053 and CBS 1000M is comparable to 9310, according to steel producers, and heat treating costs will also be comparable at temperatures below 955°C (1750°F), an increase of 10-15% in the cost of the bit is predicted by switching from 9310 to EX-00053.

Geothermal well costs are very site dependent and an improvement in penetration rate is not always the most important parameter in reducing well costs [29]. In geothermal drilling at the Geysers, bits and stabilizers made from EX-00053 or CBS 1000M, could drill 50-60% faster than conventional alloys if the weight-on-bit were increased. These high temperature bits should not only

Table 15
Cost Comparison of Steels

Steel Type	Melt Type	Base Price (\$/Kg)
4820	Air	1.13
8620	Air	0.81
9310	Air	1.19
EX55	Air	1.15
CBS 600	Vacuum	3.30
CBS 1000M	VIMVAR	9.42
EX-00053	VIMVAR	6.42
VASCO X-2M	Vacuum	10.56

penetrate faster, but less reaming would be required since they would retain gage because of their hot hardness. Use of these bits in even hotter formations than the Geysers would be even more advantageous. One computer model predicts that a 20% increase in penetration rate at the Geysers would result in a 19.8% savings in the total cost of the well[2]. Actual field test data is needed to substantiate these predicted values. Assuming that the improved bits will allow increased penetration rates and better gage control, the geothermal energy producer could very easily afford to pay a premium for the bits which would more than compensate the bit companies for the added fabrication costs.

For an initial field test it is recommended that 3-point reaming stabilizers, lugs and cones of EX-00053 be compared to identical components made from 9315 or 9310. Penetration rates comparable to conventional rock drilling should be used for both bits and the results compared with existing data for geothermal drilling. The Geysers in California would be an ideal site because of the large amount of test drilling which has already been done at that location.

CONCLUSIONS

1. Both conventional and highly wear resistant steels displayed wide variations in fracture toughness over the temperature range 22°C to 400°C. It is therefore essential to determine the fracture behavior of steels in the temperature range of operation.
2. Steels having microstructures of 100 percent tempered martensite (CBS 1000M, EX-00053, EX55 and 9315) displayed nearly constant or increasing toughness above room temperature, whereas steels containing mixed microstructures (4820, 8620, X-2M and CBS 600) decreased significantly in fracture toughness in the temperature range 100°C to 400°C.
3. EX-00053 and CBS 1000M were the only steels tested which displayed significantly higher toughness than 9315 over the entire temperature range. 9315 was superior in toughness to 4820, 8620 and EX55 over the entire temperature range. In the temperature range normally encountered at the Geysers (150-300°C), all of the steels tested have toughness at least equivalent to 4820, 8620 and EX55. If accelerated bit rotation speeds and higher loads are applied to increase penetration rates, EX-00053 and CBS 1000M are the two steels most capable of withstanding greater impact loading and bearing wear.
4. EX-00053, CBS 1000M and Vasco X-2M-#2 steels displayed an increase in toughness between 22°C and 100°C, associated with a "brittle-to-ductile" fracture transition. EX-00053-#1 increased in toughness from approximately 100 MPa $\sqrt{m}$ at room temperature to about 265 MPa $\sqrt{m}$ at 100°C. The transition temperature is sensitive to carbon content, shifting to lower temperatures with higher carbon contents.

5. The fracture toughness of CBS 1000M showed an apparent drop in toughness with increased sulfur content. Further studies on the effect of sulfur content and sulfide particle shape on K_{IC} are recommended.
6. Fatigue crack resistance measurements at 300°C for CBS 600, CBS 1000M, EX-00053 and X-2M-#1 were well within the scatter observed for 4820, 8620 and 9315 at room temperature. Although the fatigue data for these steels are limited to date, they suggest that all of the steels have enough fatigue crack resistance to withstand present geothermal drilling conditions. EX-00053 has superior fatigue crack resistance at ΔK 's less than 50 MPa $\sqrt{m}$ when compared to 4820 and 9315 at room temperature, and 9315 is clearly superior above 50 MPa $\sqrt{m}$.
7. The fatigue behaviors of CBS 600, CBS 1000M and Vasco X-2M-#2 appear to be relatively insensitive to test temperature and cycling frequency for tests conducted in air. Computerized fatigue testing is recommended to more completely characterize the fatigue behavior of these steels.
8. Bits and stabilizers of EX-00053 and CBS 1000M should be built and tested at the Geysers using conventional rock bit penetration rates to determine the advantages of using these tough, wear-resistant steels.

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APPENDIX A

HEAT TREATMENT PROCEDURES

HEAT TREATMENTS

<u>Steel Type(s)</u>	<u>Heat Treatment Code</u>	<u>Procedure</u>
4820	A	<ol style="list-style-type: none"> 1. Pseudo carburized in stainless steel envelope for seven hours at 925°C (1700°F). 2. Austenitized at 830°C (1525°F) for one hour. Water quenched with rigorous agitation. 3. Immediately tempered at 230°C (450°F) for two hours.
8620	B	<ol style="list-style-type: none"> 1. Pseudo carburized in stainless steel envelope for seven hours at 925°C (1700°F). 2. Austenitized at 850°C (1560°F) for one hour. Water quenched with rigorous agitation. 3. Immediately tempered at 230°C (450°F) for two hours.
9315	C	<ol style="list-style-type: none"> 1. Pseudo carburized for seven hours at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 2. Reheated to 815°C (1500°F) and held for 30 minutes. Oil quenched. 3. Double tempered at 175°C (350°F) for two hours each cycle.
9310M	D	<ol style="list-style-type: none"> 1. Austenitized at 845°C (1550°F) for one hour. Oil quenched. 2. Tempered at 180°C (360°F) for two hours.
EX55	E	<ol style="list-style-type: none"> 1. Pseudo carburized for two hours at 925°C (1700°F). 2. Cooled to 845°C (1550°F). Quenched into agitated oil at 65°C (150°F). 3. Tempered for 1.5 hours at 315°C (600°F).
CBS 600-#1, CBS 600-#2	F	<ol style="list-style-type: none"> 1. Pseudo carburized seven hours at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 2. Conditioned at 650°C (1200°F) for two hours. 3. Reheated in salt to 835°C (1535°F), held 25 minutes (1+30 min. total time) and oil quenched with vigorous agitation. 4. Double tempered at 315°C (600°F) for two hours each cycle.
CBS 600M-#1 CBS 600M-#2	G	<ol style="list-style-type: none"> 1. Pseudo carburized seven hours at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 2. Conditioned at 650°C (1200°F) for four hours.

<u>Steel Type(s)</u>	<u>Heat Treatment Code</u>	<u>Procedure</u>
		<ol style="list-style-type: none"> 3. Reheated to 845°C (1550°F) and held for 30 minutes. Oil quenched. 4. Cold treated at -85°C (-120°F) for two hours. 5. Double tempered at 315°C (600°F) for two hours each cycle.
CBS 600-#1	H	<ol style="list-style-type: none"> 1. Pseudo carburized for seven hours at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 2. Conditioned at 650°C (1200°F) for two hours. 3. Reheated in salt to 870°C (1600°F) and held 25 minutes (1+30 min. total time). Oil quenched with vigorous agitation. 4. Double tempered at 315°C (600°F) for two hours each cycle.
CBS 1000M-#1	I	<ol style="list-style-type: none"> 1. Preoxidized at 925°C (1700°F) for 0.5 hour. 2. Pseudo carburized for seven hours at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 3. Conditioned at 650°C (1200°F) for two hours. 4. Reheated to 955°C (1750°F) for 25 minutes at heat (105 min. total time) in a stainless steel wrap and oil quenched. 5. Cold treated at -84°C (-120°F) for three hours. 6. Double tempered at 315°C (600°F) for two hours each cycle.
CBS 1000M-#1	J	<ol style="list-style-type: none"> 1. Preoxidized at 925°C (1700°F) for 30 minutes. 2. Pseudo carburized for seven hours at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 3. Conditioned at 650°C (1200°F) for two hours. 4. Reheated in individual stainless wrap to 815°C (1550°F) for 30 minutes at heat, then heated to 1090°C (2000°F) and held for 10 minutes. Oil quenched. 5. Stress relieved at 370°C (700°F) for one hour. 6. Triple tempered at 535°C (1000°F) for two hours each cycle.
CBS 1000M-#2	K	<ol style="list-style-type: none"> 1. Pseudo carburized at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 2. Reheated to 955°C (1750°F) and held for 30 minutes. Oil quenched. 3. Cold treated at -85°C (-120°F) for two hours. 4. Double tempered at 315°C (600°F) for two hours each cycle.

<u>Steel Type(s)</u>	<u>Heat Treatment Code</u>	<u>Procedure</u>
CBS 1000M-#2	L	<ol style="list-style-type: none"> 1. Pseudo carburized at 925°C (1700°F) in stainless steel envelope and oil quenched after withdrawal from envelope. 2. Conditioned at 650°C (1200°F) for four hours. 3. Reheated to 915°C (1675°F) and held for 30 minutes. 4. Cold treated at -85°C (-120°F) for two hours. 5. Double tempered at 315°C (600°F) for two hours each cycle.
CBS 1000M-#2	M	Same as L, except tempered at 425°C (800°F) for two hours each cycle.
CBS 1000M-#3 CBS 1000M-#4	N	<ol style="list-style-type: none"> 1. Austenitized at 955°C (1750°F) for one hour. Oil quenched. 2. Double tempered at 315°C (600°F) for two hours each cycle.
CBS 1000M-#3 CBS 1000M-#4	O	<ol style="list-style-type: none"> 1. Austenitized at 910°C (1675°F) for one hour. Oil quenched. 2. Double tempered at 260°C (500°F) for two hours each cycle.
EX-00053-#1 EX-00053-#2	P	<ol style="list-style-type: none"> 1. Pseudo carburized in stainless steel envelope for seven hours at 925°C (1700°F). 2. Austenitized at 910°C (1675°F) for one hour. Oil quenched with rigorous agitation. 3. Tempered at 425°C (800°F) for one hour.
EX-00053-#2	P-2	Same as P except tempered at 315°C (600°F) for one hour.
EX-00053-#2	Q	<ol style="list-style-type: none"> 1. Pseudo carburized for seven hours at 925°C (1700°F). Air cooled. 2. Austenitized at 910°C (1675°F) in salt for one hour. Oil quenched. 3. Tempered at 315°C (600°F) for one hour.
VASCO X-2M-#1	R	<ol style="list-style-type: none"> 1. Pseudo carburized in stainless steel envelope for two hours at 1010°C (1850°F). Air cooled. 2. Austenitized at 1120°C (2050°F) for 20 minutes. Air cooled. 3. Double tempered at 315°C (600°F) for two hours each cycle.
VASCO X-2M-#1	S	<ol style="list-style-type: none"> 1. Pseudo carburized at 955°C (1750°F) for two hours. Air cooled. 2. Austenitized at 1120°C (2050°F) for 30 minutes. Air cooled. 3. Double tempered at 315°C (600°F) for two hours each cycle.

<u>Steel Type(s)</u>	<u>Heat Treatment Code</u>	<u>Procedure</u>
VASCO X-2M-#1	T	Same as S except austenitized at 1065°C (1950°F) for 30 minutes.
VASCO X-2M-#1	U	Same as S except austenitized at 1010°C (1850°F) for 30 minutes.
VASCO X-2M-#1	UU	Same as U except pack carburized for two hours at 955°C (1750°F) instead of being pseudo carburized.
VASCO X-2M-#1	V	Same as S except austenitized at 955°C (1750°F) for 30 minutes.
VASCO X-2M-#2	W	1. Austenitized at 980°C (1800°F) for 30 minutes. 2. Double tempered at 315°C (600°F) for two hours each cycle.
VASCO X-2M-#2	X	Same as W except austenitized at 955°C (1750°F) for 30 minutes.
VASCO X-2M-#2	Y	Same as W except austenitized at 925°C (1700°F) for 30 minutes.
VASCO X-2M-#2	Z	Same as W except austenitized at 900°C (1650°F) for 30 minutes.

APPENDIX B

SEM MICROGRAPHS

Figure B1. AISI 4820. Room Temperature Static Test. Ductile Fracture (300X).

Figure B2. AISI 4820 300°C Static Test. Ductile Fracture (300X).

Figure B3. AISI 8620. Room Temperature Static Test. 25-75% Brittle Cleavage (300X).

Figure B4. AISI 8620. 300°C Static Test. Ductile Fracture (300X).

Figure B5. AISI 9315. Room Temperature Static Test. Ductile Fracture (300X).

Figure B6. AISI 9315. 100°C Static Test. Ductile Fracture (300-1200X).

Figure B7. CBS 600-#1 (Heat Treatment H). Room Temperature Static Test. Ductile Fracture (100-300X).

Figure B8. CBS 600-#1 (Heat Treatment F). Room Temperature Static Test. Ductile Fracture (300X).

Figure B9. CBS 1000M-#2 (Heat Treatment K). Room Temperature Static Test. 25-75% Brittle Cleavage (300-1200X).

Figure B10. CBS 1000M-#2 (Heat Treatment K). 100°C Static Test. Ductile Fracture (300-1200X).

Figure B11. CBS 1000M-#2 (Heat Treatment K). 300°C Static Test. Ductile Fracture (300X).

Figure B12. CBS 1000M-#1 (Heat Treatment J). Room Temperature Static Test. Brittle Cleavage (300X).

Figure B13. EX-00053-#1 (Heat Treatment P). Room Temperature Static Test. Less than 25% Brittle Cleavage (300-1500X).

Figure B14. EX-00053-#1 (Heat Treatment P). 100°C Static Test. Ductile Fracture (300X).

Figure B15. Vasco X-2M-#1 (Heat Treatment R). Room Temperature Static Test. Brittle Cleavage (300X).

Figure B16. Vasco X-2M-#1 (Heat Treatment R). 100°C Static Test. Brittle Cleavage (300X).

Figure B17. Vasco X-2M-#1 (Heat Treatment R). 200°C Static Test.
Less than 25% Brittle Cleavage (300X).

Figure B18. Vasco X-2M-#1 (Heat Treatment R). 300°C Static Test.
Ductile Fracture (300X).

Figure B19. AISI 4820. Room Temperature Fatigue Test (1900X).

Figure B20. AISI 4820. Room Temperature Static Test (1900X).

Figure B21. AISI 8620. Room Temperature Fatigue Test (1900X).

Figure B22. AISI 8620. Room Temperature Static Test (1900X).

Figure B23. AISI 9315. Room Temperature Fatigue Test (1750X).

Figure B24. AISI 9315. Room Temperature Static Test (1900X).

Figure B25. CBS 600-#1 (Heat Treatment F). 300°C Fatigue Test (2000X).

Figure B26. CBS 600-#1 (Heat Treatment F). 300°C Static Test (1850X).

Figure B27. CBS 1000M-#1 (Heat Treatment I). 300°C Fatigue Test (2000X).

Figure B28. CBS 1000M-#1 (Heat Treatment I). 300°C Static Test (2000X).

(X0001) Figure B29. EX-00053-#1 (Heat Treatment P). 300°C Fatigue Test (1900X).

(X0002) Figure B30. EX-00053-#1 (Heat Treatment P). 300°C Static Test (1900X).

Figure B31. Vasco X-2M-#1 (Heat Treatment R). 300°C Fatigue Test (1000X).

Figure B32. Vasco X-2M-#1 (Heat Treatment R). 300°C Static Test (950X).

APPENDIX C

**HARDNESS PROFILES OF
SELECTED SHORT ROD SPECIMENS**

<u>Steel Type</u>	<u>Heat Treatment Code</u>	<u>Specimen Diameter, mm</u>	<u>Distance From Outer Diameter, mm</u>	<u>Hardness, R_c</u>
4820	A	50.8	0.6	37
			1.9	42
			3.9	42
			6.2	41
			8.9	40
			11.0	41
			13.7	42
			16.1	42
			18.5	40
8620	B	50.8	1.1	58
			2.2	57
			3.9	58
			5.0	59
			6.6	59
			8.7	59
			11.0	59
			16.0	59
			18.8	60
			21.1	60
			23.9	59
9315	C	25.4	0.6	34
			1.9	40
			3.1	40
			4.8	42
			6.1	43
			7.3	43
			8.8	40
EX55	E	19.1	1.0	41
			2.1	43
			3.2	43
			4.4	42
			5.1	42
			6.1	42
			6.8	42
CBS 600M-#2	G	25.4	0.6	40
			1.7	47
			3.1	47
			4.8	47
			6.2	47
			7.8	47
			9.3	48

R_a

<u>Steel Type</u>	<u>Heat Treatment Code</u>	<u>Specimen Diameter, mm</u>	<u>Distance From Outer Diameter, mm</u>	<u>Hardness, R_c</u>
CBS 1000M-#2	K	25.4	0.7	37
			1.1	39
			3.5	39
			5.4	40
			6.8	40
			8.1	42
			9.3	39
EX-00053-#1	P	50.8	1.1	31
			2.1	32
			3.8	34
			6.0	34
			9.0	34
			11.9	34
			15.8	31
			18.2	31
			21.2	31
EX-00053-#2	P	50.8	1.1	30
			2.1	32
			3.8	34
			6.0	34
			9.0	32
			11.9	32
			15.8	29
			18.2	29
			21.2	27
EX-00053-#2	P	19.1	0.9	40
			2.0	40
			3.5	39
			4.8	38
			6.2	39
VASCO X-2M-#1	R	50.8	2.3	40
			4.6	44
			6.9	44
			9.6	42
			12.8	43
			15.4	42
			18.9	41

APPENDIX D

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EX-00053

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