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LABORATORY TESTING OF PERCUSSION DRILLS FOR GEOTHERMAL APPLICATIONS

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ABSTRACT

This report describes laboratory tests of percussion drilling tools which were done at Drilling Research Lab, Salt Lake City, during February, 1980. The purpose of the tests was threefold: a) to compare the penetration rates of different hammers with each other and with conventional rotary drilling, b) to measure and compare the hammer pulses at normal and high temperatures, and c) to establish hammer life and failure modes at high temperature. Two roller bit hammers and three solid bit hammers were tested. All exhibited much higher rates of penetration in granite than were obtained with conventional rotary techniques. Tests at high temperature revealed several failure modes for the air driven hammers. Minor modifications should allow operation of these hammers at high temperature.

INTRODUCTION

The U. S. Department of Energy (DOE), Division of Geothermal Energy (DGE) is funding a program directed at developing new technology for drilling and completing geothermal wells. The goals of this program are to develop the technology required to reduce the cost of geothermal wells by 25% by 1983 and by 50% by 1987. One aspect of this program involves the development of advanced drilling systems that are capable of high rates of penetration. Percussion drilling systems are being evaluated under this program. A series of laboratory tests has recently been conducted to establish baseline performance data at ambient conditions and under high temperature conditions. This paper describes the results of these tests.

RATE OF PENETRATION MEASUREMENTS

For the ROP measurements, two "oilfield" hammers were rented and three "industrial" hammers were bought. Both types use the same principle of a reciprocating piston striking an anvil, but the oilfield tools are threaded to accept a conventional roller bit, while an industrial tool uses a one-piece solid bit with tungsten carbide inserts. General descriptions of the hammers are given in Table 1.

Table 1

General Descriptive Data on Hammers

Hammer	Hammer Diameter cm (in.)	Bit Diameter cm (in.)	Length with Bit cm (in.)	Length without Bit cm (in.)	Weight kg (lb)	Operating Air Pressure Range kPa (psi)	Air Consumption at 1 724 kPa (250 psi) (Blank Choke) m^3/s (ft^3/min) (standard)
TRW- Mission A63-15	16.2 (6.375)	20.3 (8.0)	159.9 (60.2)	139.7 (55.0)	159 (350)	690-1 724 (100-250)	0.51 (1 090)
TRW - Mission Hammerdrill	17.2 (6.75)	20.0 (7.875)		177.8 (70.0)	259 (570)	690-2 413 (100-350)	0.49 (1 040)
Ingersoll-Rand BHD 360	13.7 (5.375)	21.6 (8.5)	129.5 (51.0)		98 (215)	1 034-2 413 (150-350)	0.27 (570)
Ingersoll Rand BHD 2076	16.8 (6.625)	20.0 (7.875)		193.4 (76.1)	238 (525)		
Epley B-2	17.2 (6.75)	20.3 (8.0)	144.8 (57.0)		145 (320)	690-1 724 (100-250)	0.50 (1 070)

The baseline for hammer penetration rate comparison was the data from a Reed M-70 7-7/8" insert bit run without hammer over a range of weights on bit and rotary speeds. This baseline data is plotted in Figure 1. Each of the hammers was then run in samples of the same granite. The oilfield hammers used the same Reed bit as the baseline tests and each of the industrial hammers used the bit with which it was equipped by its manufacturer.

The bits used in the industrial hammers are one-piece steel bodies with hemispherical tungsten carbide inserts (Figure 2). The inserts are quite strong in compression but not in shear, so they can withstand heavy blows from the hammer but not high torques imposed by high weight on bit. The WOB was held constant at 5000 lb (approximately manufacturers' recommendation) for all three industrial hammers, and the air supply pressure and rotary speed were varied. The inserts in the roller bit do not experience the same kind of shear loading, so these assemblies can be run at higher WOB values. For the roller-bit/hammer tests, the rotary speed was held constant at 45 rpm and the air supply pressure and WOB were varied. The rates of penetration are plotted for difference conditions in Figures 3-4.

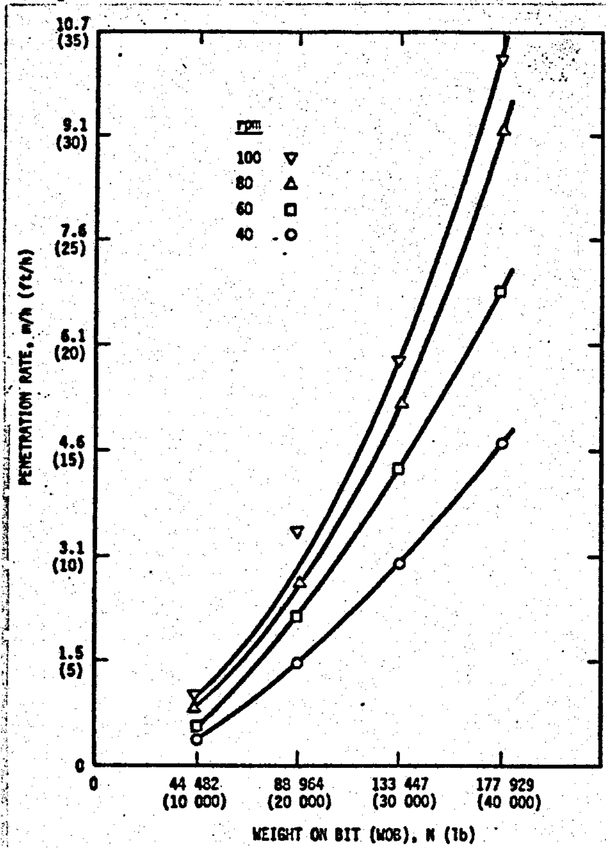

Figure 1. Baseline Data from Reed 20-cm (7.875-in.) M-70 Tungsten Carbide Insert Bit; Rock - Sierra White Granite; Air Flow Through Bit - 0.38 m^3/s (800 ft^3/min, Standard)

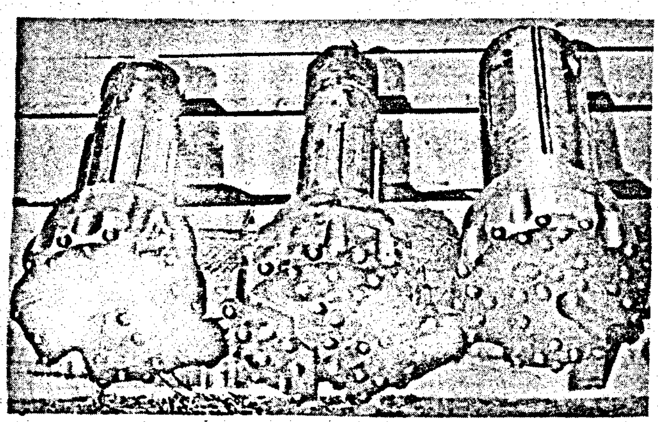

Figure 2. Bits used in Industrial hammers; left to right -- Mission, Ingersoll-Rand, Epley

Figure 3 shows that the ROP of the oilfield hammers increased only slightly for large increases in bit weight. This is because the force of the hammer blows is greater than the steady bit weight, and the change in bit weight is small compared to the total force of hammer blow plus bit weight. This behavior is also consistent with manufacturers' recommendations to operate the hammers with relatively low WOB.

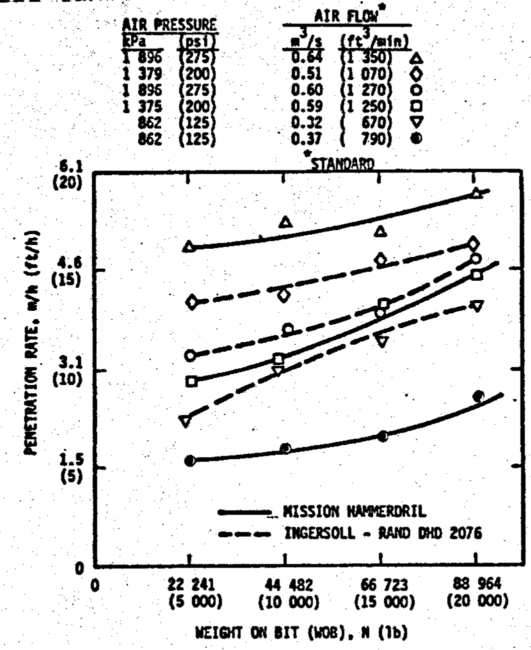

Figure 3. Penetration Rates of "Oilfield" Hammers with Reed, 20-cm (7.875-in.), M-70 Bit; Run at Varying Air Pressure and Weight on Bit; Rock - Sierra White Granite

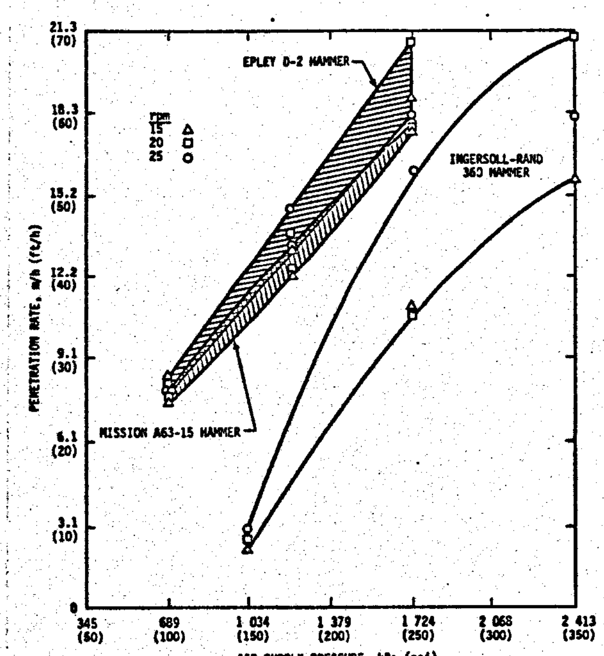

Figure 4. Rates of Penetration for Industrial Hammers; Operating Envelopes Show Variance in Rates of Penetration Over Range of Air Pressure and Rotary Speed; Rock - Sierra White Granite

Large changes in ROP are seen in Figure 3 when the pressure of the air supply to the hammers is increased. When the pressure is raised, both the hammer blow frequency and the energy per blow are increased. If we assume that there is a certain specific energy required to break a unit volume of rock, then the ROP should increase as the 3/2 power of the air pressure, and with one exception, the curves in Figure 3 show good agreement with this ratio. The exception is the 275 psi line for the I-R hammer, which shows lower ROP than the 200 psi line for the same tool. The reason for this is not known, but a tentative explanation is suggested by the failure of this hammer in the next phase of testing. When an attempt was made to run the I-R 2076 against a load cell, it would not operate at all. It appears that an internal air valve in the hammer had malfunctioned. The hammer was not disassembled to verify this, but it seems likely that this failure mode could have been initiated during the 275 psi ROP test.

The average ROP of the hammers at 200 psi and 20,000 lbs WOB was approximately 15 ft/hr; this compares with a ROP of 5 ft/hr for the same bit run without percussion at the same WOB and rotary speed.

It is commonly stated that hammers reduce drill string vibration in rough drilling conditions. Although there is considerable field experience to verify this in highly faulted formations, it is apparently not true in competent rock such as the granite samples used in these tests. Tables 2 and 3 show the high frequency variations in torque and axial force measured by the strain-gaged sub in the DRL drill string. In general, the standard deviation of each variable is higher with the hammer than without. This seems reasonable for the laboratory situation, but faulted formations and a longer, more flexible drill string might produce very different behavior.

The penetration rates of the industrial hammers are shown in Figure 4, plotted as envelopes of operating conditions. At each air supply pressure, penetration rates at different rotary speeds are plotted and curves are drawn through the minimum and the maximum points. This provides an envelope for each tool that shows its penetration rate as well as its sensitivity to rotary speed.

As the figure shows, the industrial hammers have considerably higher penetration rates than the oilfield hammers running at about the same air supply pressures and flow rates. This is primarily due to the much more efficient energy transfer

Table 2

Comparison of Axial Force and Torque in the Drill String Operating with and without Hammer at Equal Weight on Bit and Rotary Speed

Nominal Weight on Bit N (lb)	M-70 Without Hammer 40 Rpm	Mission with Hammer, 80 Rpm — Air Pressure, kPa (psi) 862 (125)	1 379 (200)	1 896 (275)
	Measured Weight on Bit, N (lb)*			
44 482 (10 000)	44 731/6 632 (10 056)/(1 491)	44 536/18 914 (10 012)/(4 252)	39 429/27 112 (8 864)/(6 095)	39 291/29 367 (8 833)/(6 602)
88 964 (20 000)	88 867/9 799 (19 978)/(2 203)	87 639/25 840 (19 702)/(5 809)	86 500/37 401 (19 446)/(8 408)	72 035/32 530 (16 194)/(7 313)
	Torque, N·m (lbf-ft)*			
44 482 (10 000)	305/123 (225)/(91)	388/128 (286)/(94)	480/243 (354)/(179)	697/285 (514)/(210)
88 964 (20 000)	629/209 (510)/(154)	898/420 (662)/(310)	1 192/224 (879)/(165)	1 199/350 (884)/(250)

*Values = Linear Intercept/Standard Deviation

Table 3

Comparison of Axial Force and Torque in the Drill String Operating with and without Hammer at Equal Rate of Penetration 5.5 m/h (18 ft/h)

	Mission Hammerdrill	M-70 without Hammer 40 Rpm 177 929 N** (40 000 lb)	M-70 without Hammer 80 Rpm 133 447 N** (30 000 lb)
Axial* Force N (lb)	72 035/32 530 (16 194)/(7 313)	175 665/12 740 (39 491)/(2 864)	135 738/18 954 (30 515)/(4 261)
Torque* N·m (lbf.ft)	1 199/350 (884)/258)	1 969/365 (1 452)/(269)	1 196/258 (882)/(190)

*Values = Linear Intercept/Standard Deviation

**Nominal Weight on Bit

from the reciprocating piston to the rock through the solid one-piece drill bit. In the oilfield hammer the piston is transmitted to the driver sub, through a threaded connection to the bit body, and through the bit bearings to the cones. This system is much less rigid and therefore less efficient than the solid bit.

It is also apparent that there is a wide variation in penetration rate with rotary speed for some drilling conditions. The variation is not only wide but inconsistent, because the penetration rate does not always increase with rotary speed. The reason for this is not completely clear, but it seems to be a function of penetration per revolution, angular spacing of the gage carbides, and formation being drilled.

Figure 4 also shows that the penetration rate of the industrial hammers does not increase as the 3/2 power of the air supply pressure, which theory predicts. The penetration rate (and blow frequency) below theoretical values are primarily caused by the increasing back pressure at the piston exhaust position. The flow restriction imposed by the air passage through the bit shank becomes more important as flow rate increases, and therefore raises the pressure into which the piston exhausts.

PULSE MEASUREMENT TESTS

An attempt was also made to compare the pulse characteristics (shape, amplitude, and frequency) of the industrial and the oilfield hammers and to compare the pulse characteristics of the industrial hammers at high and at normal temperatures. This data would have shown the force of the blows delivered to the rock by the different hammers and whether the performance of the hammers changed significantly at high temperature.

The test set-up had a strain-gaged load cell beneath the bit and accelerometers mounted on the bit head. One oilfield and two industrial hammers were run in this set-up. Net results were the destruction of two load cells and five accelerometers and the collection of essentially no useful data. The primary reason for this was the unexpected magnitude of the loads on the transducers. These very high loads were apparently caused by the dynamic separation of the bit and the load cell plate with their subsequent impact as they rebounded back together. Some of the broken accelerometers were rated for 50,000 g service, indicating loads in excess of this amount.

HIGH TEMPERATURE TESTS

The objectives of this part of the testing were to verify high temperature operation of the industrial hammers and to identify any failure modes unique to the high temperature operation. The test set-up was similar to that for normal rock drilling, except that the drilling target was a cast iron billet and the air supply was heated by passing through a gas-fired heat exchanger. The test plan was to operate the hammers for eight hours at each temperature increment of 50°F from 350°F to 500°F. At the end of each eight-hour operating period, the air supply temperature would be cycled to ambient and back to hot -- with the hammer off bottom -- to simulate tripping.

The first hammer tested was the Mission A63-15. The bit was placed against a cast iron billet and the hammer was brought to 350°F over a one-hour period by passing hot air through it. Rotation was started and the hammer was loaded to close the bit and begin drilling while maintaining the hot air flow. After about four minutes the hammer stopped; it was cooled by passing ambient air through it and was then disassembled. The Delrin foot valve in the top of the bit had shattered into approximately ten pieces, causing the piston to stop reciprocating.

The Ingersoll-Rand DHD 360 was tried next -- we believed that since it had a metal foot valve it would last longer at high temperature. The same starting procedure was used and the I-R tool drilled for approximately three minutes before stopping. When the hammer was disassembled, the foot valve was found to be crushed and could be lifted easily out of the bit. Apparently the valve is held in place by a material which melted or softened enough to create misalignment of the valve tube and it was crushed by the piston.

While the I-R test was being prepared, the DRL machine shop made an aluminum (6061-T6) tube to replace the failed part in the Mission A63-15. The hammer was assembled and the test repeated; the hammer ran for 52 minutes before stopping. The problem was once again the foot valve. It apparently had fatigued, since it had parted very cleanly just at the point where the OD increased to form a positioning feature on the tube. This problem may have been aggravated by a tool mark on the tube surface at the failure point.

Because of these failures, the Epley hammer, which has a plastic feed tube inside the piston as well as a plastic foot valve in the bit, was not tested at 350°F.

During each of the high temperature tests, the air temperature was measured at the hammer intake and exhaust. The exhaust air became significantly cooler once hammering began and the air expansion in the piston replaced the orifice expansion of the temperature soak period. Both hammers produced expansion cooling of approximately 48°F, which could be significant in keeping the operating temperature low in a hot wellbore.

CONCLUSIONS

These test results indicate that off-the-shelf industrial hammers will not operate at geothermal temperatures, but that there is no fundamental obstacle to their modification. Replacing the plastic valve parts with a more durable material is not a trivial problem, because it is very important that the parts have a fatigue-resistant resilience similar to plastic. This design work will be done if a study of drilling economics shows that percussion's high rate of penetration justifies further development.

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