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Evaluation of Water-Jet-Assisted Drilling With Handheld Drills

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	lbf	pound (force)
ft•lbf	foot pound (force)	lbf/ft^3	pound (force) per cubic foot
ft•lbf/in^3	foot pound (force) per cubic inch (specific energy)	lbf/in^2	pound (force) per square inch
ft•lbf/s	foot pound (force) per second	min	minute
gal/min	gallon per minute	pct	percent
hp	horsepower	ppv	part per volume
in	inch	r/min	revolution per minute
in/s	inch per second	s	second

EVALUATION OF WATER-JET-ASSISTED DRILLING WITH HANDHELD DRILLS

By P. D. Kovscek,[1] C. D. Taylor,[2] and E. D. Thimons[3]

ABSTRACT

The Bureau of Mines has tested a low-thrust water-jet-assisted rotary drill. This work was performed to evaluate the performance of a water-jet-assisted drill operated at thrust levels typical of a handheld manual-thrust operation. Prior work by the Bureau had indicated that using water-jet assist with high-thrust drilling applications would increase drilling rate.

Small-diameter holes were drilled in five different types of rock. Thrust and water pressure were varied as the drill rate was monitored. The test results indicate that drilling rates increase with increasing water pressure and thrust. The water jet has more effect on reducing the specific energy when drilling in the harder rocks than in softer rocks. Variation in drill rate for a given rock sample is attributable primarily to the material heterogeneity within the sample. One rock type (Greenwich sandstone) could not be drilled efficiently with the water-jet-assisted drill.

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[3] Supervisory physical scientist, Pittsburgh Research Center.

INTRODUCTION

BACKGROUND

Most small-diameter holes drilled during underground mining operations are for bolts that provide roof and rib support. Other small-diameter holes are drilled for explosives used for blasting and for hangers used to suspend trolley wires and belt anchors. Most of the holes are drilled with rotary drills. These drills use tungsten carbide bits to supply mechanical energy to the rock surface. Penetration of the rock occurs when the bit supplies enough cutting and normal force to fragment the rock surface. Within limits the drilling rate increases as the normal and cutting forces increase. To maintain drilling rate in harder rock the bit forces must be increased.

Machine-mounted rotary drills are used to drill many holes for roof and rib support. Thrust supplied through the drill rod can be increased to maintain the drilling rate when harder rock is encountered. However, the thrust level is limited by the strength of the drill rod. Increasing the thrust may also result in rapid deterioration of the bit tip.

PRIOR STUDIES

Earlier work (1-4)[4] investigated a technique to maintain the drilling rate in harder rocks without increasing the thrust. The technique, known as water-jet-assisted drilling, uses high-pressure streams of water (water jets) with a rotary drill. The water jets are directed from nozzles in the drill bit retainer so that mechanical and fluid energy are delivered to the same location on the rock surface. The rock surface is eroded by the water jets and ridges are formed. The free surface of the ridges enhances the ability of the mechanical bit to fragment the rock.

The studies were performed to determine if the use of water-jet assist would improve the performance of a machine-mounted rotary drill. To simulate operation of a machine-mounted drill, a test apparatus was used to provide thrust levels of 250 lbf (2) or greater. Results of these tests indicated that the machine-mounted rotary drill with water-jet assist could maintain the same drill rate in harder rock without increasing the thrust. Also the water-jet-assisted drill had the potential to drill faster than a conventional machine-mounted drill operating dry. In extremely hard rock strata, the performance of the water-jet-assisted drill, relative to the drill rate and bit life, was roughly comparable to that of a conventional percussive drill.

CURRENT STUDY

Small-diameter holes must also be drilled in areas that are inaccessible to a machine-mounted drill. In these cases it may be necessary to use a handheld drill. Thrust for a handheld drill is limited by the strength of the individual worker. If the thrust is not sufficient to drill a hard-rock strata, a percussive-type (stoper) drill, rather than a rotary drill, is often used. However, the stoper drill is noisy, and because of its size and weight, can be difficult to use. A rotary drill is quieter, lighter in weight, and requires less energy. Therefore in soft to medium-hard sandstones, use of a rotary rather than a percussive drill is preferred.

The prior studies of water-jet-assisted rotary drills, described above, were designed to evaluate drill performance at thrust levels greater than what can be provided with a handheld drill. Use of water-jet assist, with a rotary handheld drill, has the potential to enable more effective low-thrust drilling in harder rocks. Hardware for such a system is available. The objective of this study was to determine if the performance of a rotary drill could be improved by using water-jet assist. The criteria for drill performance was based on drilling rate and specific drill energy. Test

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[4] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

conditions simulated drilling in five different rock types at thrust levels typical of a handheld rotary drill operation.

ACKNOWLEDGMENTS

The authors acknowledge the assistance provided by the following Boeing Services personnel, Pittsburgh, PA, who aided in the design and construction of test equipment: J. Leslie Thompson, senior project engineer; Allen Constantine and A. Wayne Himler, engineering technicians, and Ed Uranker, mechanical technician. The ergonomics evaluation of manual thrust capability for a handheld drill was conducted by Sean Gallagher, research physiologist, Bureau of Mines, Pittsburgh, PA.

EXPERIMENTAL PROCEDURE

TEST APPARATUS

The test apparatus was constructed using components compatible with a handheld drill. These components included a hydraulic motor, rotary swivel, drill steel, and control valves. The hydraulic drill motor operated from a 1,500- to 2,000-lb/in^2 source with a maximum flow rate of 6 gal/min; it produced 12 ft•lbf of torque, at a rotational velocity of 400 r/min.

High-pressure water for the water jets was supplied by dual hydraulic oil-powered double-acting intensifiers with a 13:1 intensification ratio and rated maximum water flow of 2.5 gal/min. A 150-hp, 50-gal/min pressure compensated pump supplied hydraulic oil pressure up to 2,500 lbf/in^2 to the intensifiers.

The test apparatus, intensifier, and pressure-compensated pump were mounted on a crawler driven chassis. The chassis had a mounting plate that could be moved vertically. The drill was placed on a low-friction linear-bearing slide and retaining assembly attached to the mounting plate (see figure 1). Four holes drilled in a vertical pattern were spaced approximately 4 in. apart. The test unit was moved via the crawlers to the next position where the vertical pattern was repeated.

A 35,000-lbf/in^2 working pressure hose delivered the water to a rotary swivel that was attached to the drill steel. The high-pressure water was transferred from the swivel through the drill steel to four sapphire nozzles located in the bit retainer (fig. 2). The inner jets (0.009 in diam) were directed to cut concentric rings at the bottom of the drilled hole, while the outer jets (0.012 in diam) cut kerfs at the periphery of the drilled hole. A 0.94-in-diam bit cap was installed over the end of the bit retainer. The bit cap had four holes through which the water passed from the nozzles to the surface of the rock being drilled. The bit cap was positioned and held in place by a cap lock stud. The distance from the nozzle exit to the drill bit tip was approximately 0.75 in.

EXPERIMENTAL DESIGN

The experimental design used thrust and water pressures at two discrete levels with single replication. The test matrix is given in table 1. The order of testing was randomized. Also centerpoint tests (22,500 lbf/in^2 water pressure, 50 lbf thrust) were run with three replications.

A total of 12 holes were drilled in each rock. Two bits were used for each rock type. Use of each bit was divided equally (six holes) between the replicated tests. Maximum hole depth was 20 in.

ROCK SAMPLES

The rock samples tested included sandstone (three types), coalcrete, and trona. A Schmidt hammer survey was

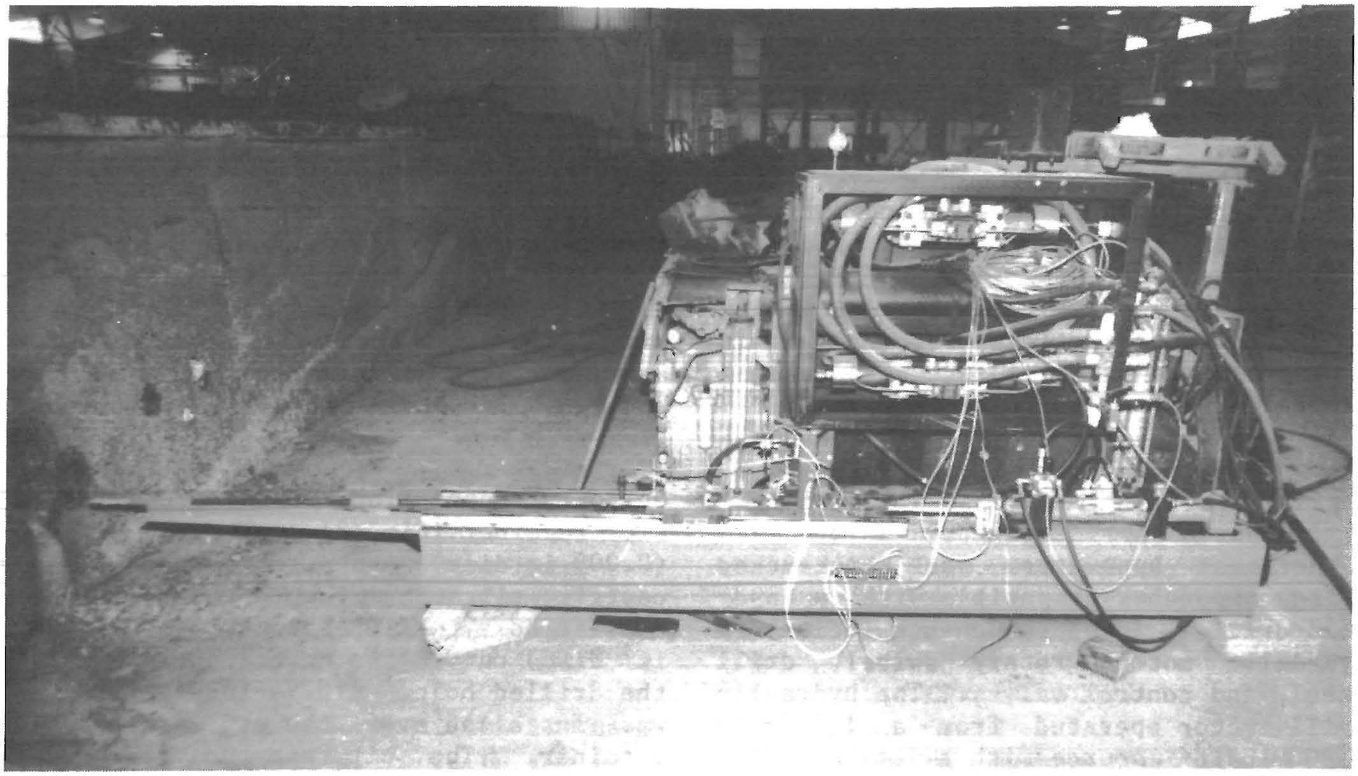

FIGURE 1.–Rock drill slide and retaining assembly.

performed on the rock samples to obtain a relative indicator of compressive strengths. The compressive strength for the rocks tested ranged from 4,300 to 22,000 lbf/in^2 (table 2). Additional information about the rock types used is given in appendix A.

TABLE 1. - Test matrix for drill tests

	20 lbf (-)	80 lbf (+)
30,000 lbf/in^2 (+)	+ -	+ +
15,000 lbf/in^2 (-)	- -	- +

TABLE 2. - Density and hardness of materials tested

Rock type	Density, lbf/ft^3	Compressive strength, lbf/in^2
Berea.............	130	9,000
Coalcrete.........	106	4,300
German............	156	19,000
Greenwich.........	163	22,000
Trona.............	134	9,900

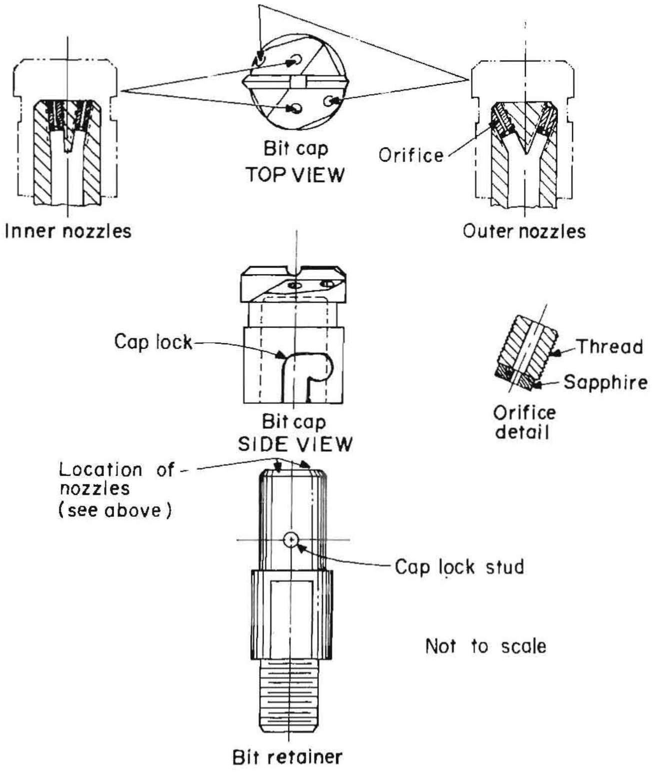

FIGURE 2.–Bit retainer, bit cap, and nozzles.

INSTRUMENTATION AND DATA COLLECTION

The slide and retaining assembly (fig. 3) were designed to measure the drill thrust and reacted torque forces using force-sensing load cells. The thrust load cell was installed between the drill and slide retaining assembly to eliminate measurement of the friction of the slide. A roller bearing was installed on the rear of the drill to enable a positive reaction point for the torque force measurement. The torque force load cell (fig. 3) was provided with ball and tie rod attachment points to minimize interaction of the thrust and torque force measurements.

The applied thrust was controlled by the drill operator using an adjustable pressure-reducing valve that was installed in the thrust hydraulic cylinder oil line. The dc voltage output from the thrust load cell was displayed on a digital voltmeter that enabled the drill operator to set and maintain a constant applied thrust level. During each test, the drill operator adjusted the thrust levels to diminish thrust force inconsistencies due to sample variation. Calculations involving thrust used the average thrust levels measured during each test.

In addition to thrust and reacted torque, the torque energy supplied by the drill and the fluid energy supplied by the water jets were measured. The hydraulic oil pressure and flow rate were monitored by installing a pressure transducer and flowmeter in the supply line to the drill motor. The water pressure was determined using a standard pressure gauge installed on the hydraulic oil low-pressure side of the intensifier. Water-jet pressures were calculated using the intensification ratio of 13:1. A water flow meter was installed in the water supply line (adjacent to the water inlet) to measure the quantity of water supplied to the drill bit.

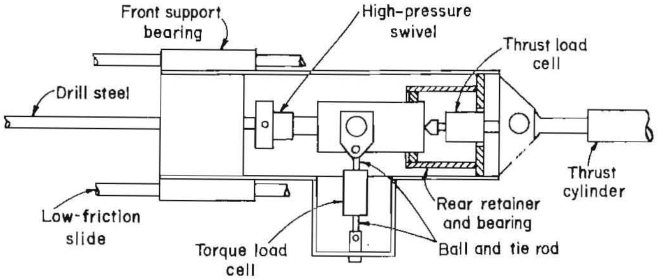

FIGURE 3.–Drill-mounted torque and thrust assembly.

To calculate the drill penetration rate, a wire-pull linear displacement transducer was installed on the low-friction slide assembly. The rotation rate (revolutions per minute) of the drill steel was measured with a tachometer.

Signal conditioning was accomplished with amplifiers for the strain gauge transducers, and with frequency to analog converters for the pulsed output transducers used to monitor revolutions per minute and flow. All signals were scaled to a dc voltage. The analogous dc voltage was recorded on an FM magnetic tape recorder and a strip-chart recorder. A block diagram of the instrumentation system is shown in figure 4.

SELECTION OF THRUST AND WATER PRESSURE LEVELS

Thrust levels were selected based on the average force a worker could exert on a handheld drill when used in the underground environment. An ergonomic evaluation, conducted by the Bureau of Mines,[5] concluded that the average person could exert a force of 50 lbf for a period of 1 min. Therefore three levels of force, 20, 50, and 80 lbf, were selected for the drill thrust. These thrust levels included the range of conditions that might be encountered underground.

Water pressures between 15,000 and 30,000 lbf/in^2 were selected for the testing program. It was anticipated that water pressures from 15,000 to 30,000 lbf/in^2 would be required to erode the surface of the test rocks. Also water at this pressure could be provided by the intensifiers and safely transported by the available high-pressure hose. The

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[5] A summary description of the ergonomic evaluation is given in appendix B.

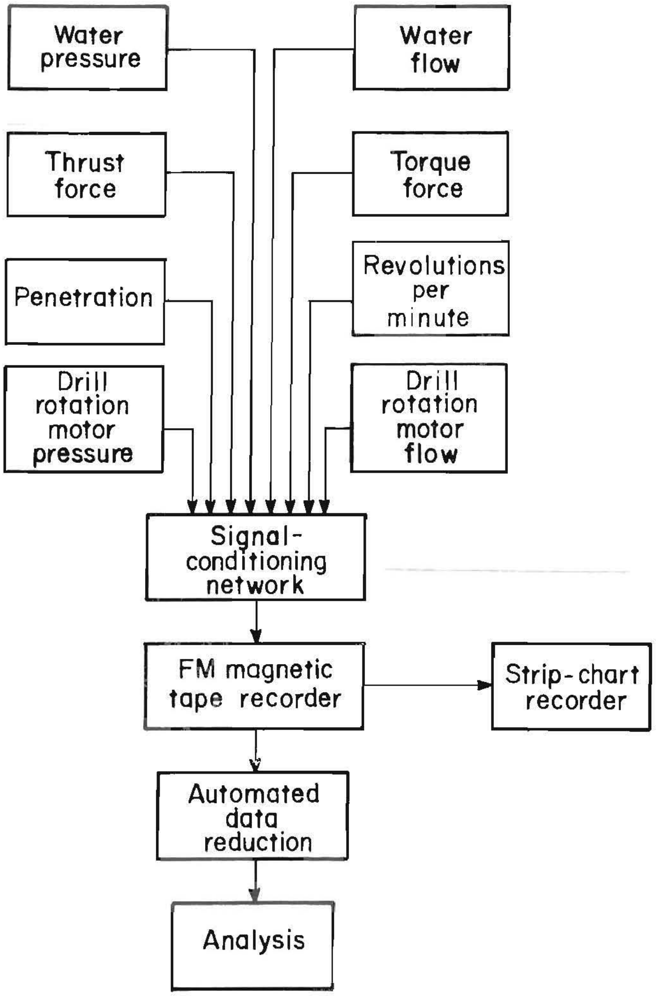

FIGURE 4.–Rotary drill data collection system.

average water flow rates were 1.13, 1.42, and 1.72 gal/min for pressures of 15,000, 22,500, and 30,000 lbf/in^2, respectively.

DATA REDUCTION

The transducer outputs recorded on magnetic tape were replayed into an analog to digital converter and scaled in engineering units. The sample rate was varied to allow for the difference in drill time for the different rocks. Twenty measurements per second were taken while drilling the Greenwich and German sandstones. Fifty measurements per second were taken during the drilling of all other stone samples.

No data were collected at the start or near the end of the test hole so that the measurements obtained corresponded to steady-state conditions. The data were averaged and the following equations were used to derive drill rate, reacted torque, torque, water, and thrust energies, and specific energy.

Drill rate (R)

$$R = D/t, \quad \text{in/s} \qquad (1)$$

where D = length of drill hole, in,

and t = time of test, s.

Reacted torque (Tr)

$$Tr = 0.555 * (TF), \quad \text{ft·lbf} \qquad (2)$$

where 0.555 = the distance of the transducer from the centerline of the drill, ft,

and TF = measured output of the torque load cell, lbf,

Torque energy (TQ)

$$TQ = \frac{P_h * Q_h * 550 * (TF)}{1{,}714}, \quad \text{ft·lbf} \qquad (3)$$

where P_h = drill motor, rotational hydraulic pressure, lbf/in^2,

Q_h = drill motor hydraulic flow, gal/min,

and t = time of test, s.

Water energy (W)

$$W = \frac{P_w * Q_w * 550 * t}{1{,}714}, \quad \text{ft·lbf} \qquad (4)$$

where P_w = water pressure, lbf/in^2

Q_w = water flow to drill, gal/min,

and t = time of test, s.

Thrust energy (T)

$$T = \frac{F * D}{12}, \quad \text{ft·lbf} \qquad (5)$$

where F = average force applied, lbf,

and D = length of drill hole, in.

TABLE 3. — Analysis of variance: drill rate versus applied thrust and water pressure

Rock type	Source	SS	DF	MS	F	SL	R^2	SDR
Berea......................	Reg	0.659	2	0.3296	55.87	0.0001	0.93	0.077
	Res	.053	9	.0059				
Coalcrete.................	Reg	.782	2	.3908	14.14	.0010	.69	.166
	Res	.359	13	.0276				
German.....................	Reg	.070	2	.0349	62.33	.0001	.93	.024
	Res	.005	9	.0006				
Greenwich.................	Reg	.0008	2	.00042	28.65	.0010	.86	.0038
	Res	.0001	9	.00002				
Trona......................	Reg	.965	2	.4823	54.04	.0001	.92	.094
	Reg	.080	9	.0089				

DF	Degrees of freedom	Reg	Regression	SL	Significance level
F	F-ratio value	Res	Residual	SS	Sum of squares
MS	Mean square	SDR	Standard deviation of regression		
R^2	Multiple R square				

Specific energy (SE)

$$SE = \frac{T + TQ + W}{\pi * r^2 * D}, \quad \frac{ft \cdot lbf}{in^3} \qquad (6)$$

where T = thrust energy,

TQ = torque energy,

W = water energy,

r = nominal radius of the bit, in,

and D = length of drill hole, in.

A multiple linear regression was performed with thrust, water pressure, and the thrust-water pressure interaction as the dependent variables and drill rate as the dependent variable. The data for each rock tested were processed using a multiple linear regression algorithm and a backward elimination method. The algorithm is contained in an RS/1[6] software package, which was run on a VAX 780 computer. The algorithm is based upon a standard multiple regression technique (5).

By the least squares method, the multiple regression algorithm fits a plane to the data such that the difference of the predicted data points to the observed data points is a minimum. The significance level, F-ratio tests, and R^2 values shown in table 3 signify real predicted values of drill rate.

RESULTS

Table 4 gives the average drill rates and specific energies for the five rock types tested at each selected level of water pressure and thrust. The measured operating parameters for each individual test (in the order in which they were conducted) are given in appendix C. The measured parameters were used to calculate the specific energy.

The technique of multiple regression was used to determine the plane of best fit for the drill rate data. Predicted values of drill rate were determined from the plane of best fit. The lines in figures 5 to 9, for 15,000 22,500, and 30,000 lbf/in^2 water pressures, show the relationship of drill rate to thrust for varying thrust levels. The lines were drawn using the predicted drill rate values. For each rock type drilled, the measured drill rates are also shown on figures 5 to 9. The figures show that the average drilling rate increased with thrust and water pressure.

Figure 10 gives the results from the centerpoint tests that used thrust and

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[6] Reference to specific products does not imply endorsement by the Bureau of Mines.

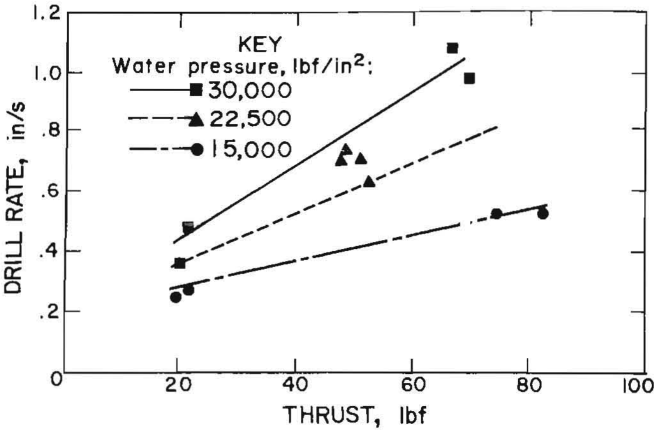

FIGURE 5.–Drill rate versus thrust–Berea sandstone.

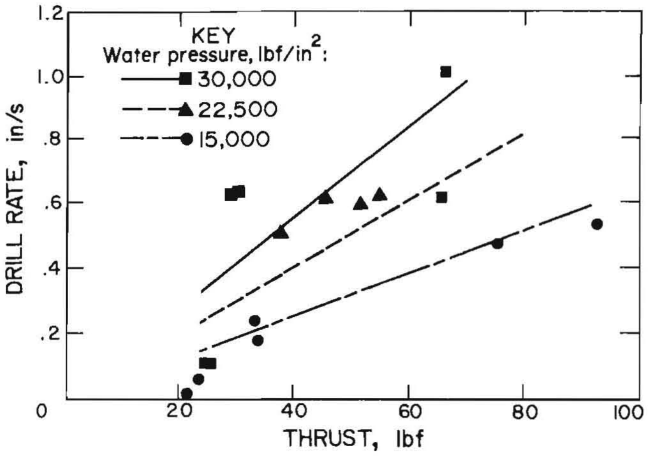

FIGURE 6.–Drill rate versus thrust–coalcrete.

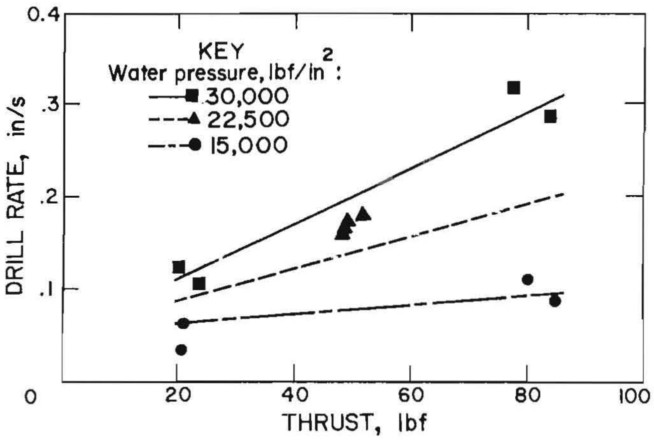

FIGURE 7.–Drill rate versus thrust–German sandstone.

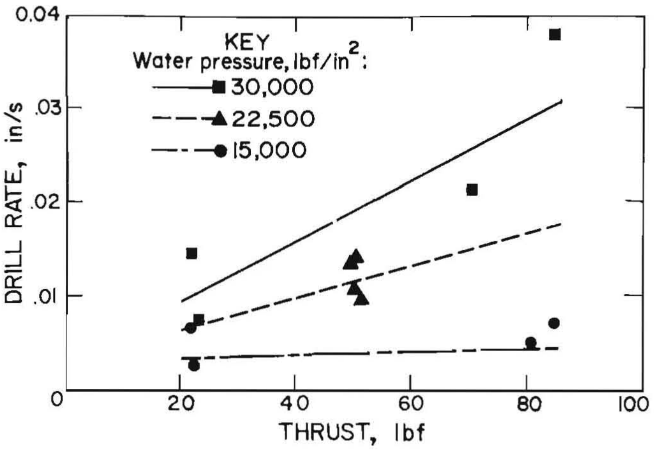

FIGURE 8.–Drill rate versus thrust–Greenwich sandstone.

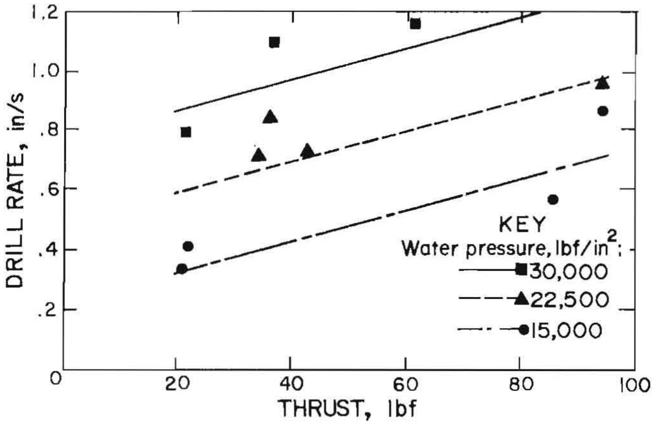

FIGURE 9.–Drill rate versus thrust–trona.

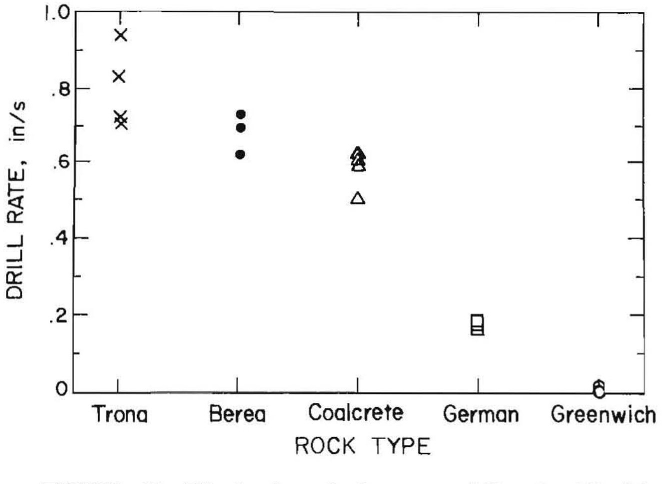

FIGURE 10.–Effect of rock type on drill rate (50 lbf thrust, 22,500 lbf/in^2 water pressure).

TABLE 4. - Handheld high-pressure drill test results

Rock type	Thrust, lbf	Water pressure, 10^3 lbf/in^2	Drill rate, in/s	Specific energy, 10^3 ft·lbf/in^3
Berea	20	15	0.255	39.3
	20	30	.419	64.7
	50	22.5	.683	25.2
	80	15	.519	19.5
	80	30	1.918	26.1
Coalcrete	20	15	.040	318.1
	20	30	.109	229.6
	30	15	.205	48.5
	30	30	.623	40.1
	50	22.5	.574	28.6
	80	15	.496	20.1
	80	30	.802	32.8
German	20	15	.048	235.1
	20	30	.115	236.4
	50	22.5	.168	105.8
	80	15	.098	108.6
	80	30	.297	95.5
Greenwich	20	15	.005	2,779.9
	20	30	.011	2,723.8
	50	22.5	.012	1,566.6
	80	15	.006	1,806.5
	80	30	.209	1,034.7
Trona	20	15	.372	28.8
	20	30	.938	30.3
	50	22.5	.799	23.0
	80	15	.707	16.0
	80	30	1.281	22.0

water pressure settings of 50 lbf and 22,500 lbf/in^2. Drill rate was highest for the trona rock and lowest for the Greenwich sandstone (fig. 10). The Greenwich sandstone could not be drilled efficiently even at 80 lbf thrust and 30,000 lbf/in^2 water pressure.

For all the rock types tested, the highest drill penetration rates were achieved at the 80 lbf thrust and 30,000 lbf/in^2 water pressure. Generally, the drill rates increased with increased thrust or water pressure. However, the water pressure had less effect on the drill rate at the lower thrust levels. Except for trona, at the higher thrust levels the drill rate increased more than would be expected for increases in thrust or water pressure separately.

The data in table 4 show that, for a given water pressure, the specific energy decreased as thrust increased. The magnitude of the change in specific energy was affected by both the rock type and the thrust level.

The most efficient drill operation, i.e., the lowest drill energy consumed per cubic inch of removed material, was at the 80-lbf applied thrust level. The specific energy per cubic inch increased for the trona, coalcrete, and Berea sandstone at the 80-lbf thrust with an increase of water pressure from 15,000 to 30,000 lbf/in^2 (see table 4). However, the specific energy decreased for the Greenwich and German sandstones with an increase in water pressure at the 80-lbf applied thrust level.

DISCUSSION

EFFECT OF THRUST AND WATER PRESSURE

An analysis of the linear model used for the multiple regression indicates that varying either thrust or water pressure has a significant effect on the drill rate. In addition, there is a significant positive, first-order interaction effect due to thrust and water pressure. This means that the drill rate increases more than expected for individual increases in either thrust or water pressure. The effect of the interaction can be seen in figures 5 to 8. The water-jet assist was more effective in increasing drill rate at the higher (80 lbf) thrust level and less effective at the lower thrust levels.

The only time the water pressure thrust interaction was not significant was while drilling in trona (fig. 9). The effect of water pressure on drill rate was approximately the same at high and low thrust levels. This is attributed to the water solubility of trona, which dissolves on contact with water at any pressure.

DRILL SPECIFIC ENERGY

The specific energy is determined by the energy required for the drill to remove a specified unit volume of material (6). The specific energy, in addition to drill rate, is another indicator of drilling efficiency. Reducing the specific energy improves drill efficiency. At a constant drill energy, the specific energy decreases with an increase in the penetration rate. When one rock type is drilled with a variable energy supply, the specific energy increases or decreases, depending on the ability of the additional energy to fragment the rock.

The volume of removed material is a function of hole diameter and drill rate. The calculated specific energy values are a function of the drill energy supplied and the volume of material removed. Holes drilled in German and Greenwich sandstones were approximately the same diameter as the bit cap. Holes drilled in the softer rocks (trona, Berea sandstone) were larger than the bit cap diameter, particularly at the beginning of the hole. For the calculation of all specific energies, the hole diameter was taken to be equal to the bit cap diameter (0.94 in).

The hole size was a function of drill rate, rock type, thrust, and water pressure. If a larger diameter hole were formed, the effect would be to reduce the calculated specific energy value. If the larger diameters of the holes drilled in the Berea sandstone and trona were used for calculating specific energy, the values calculated for these rocks would have been smaller. However, this decrease in specific energy would not be considered an indication of improved drilling efficiency because there is no advantage in having a larger diameter hole. Therefore, since the potential benefits of using water-jet-assisted drilling are related to drilling rate rather than hole diameter, the same hole diameter (15/16 in) was used to calculate specific energy for all rock types.

Curves were drawn to show the relationship between specific energy and drill rate for Berea and Greenwich sandstones in figures 11 and 12, respectively. These rocks were chosen to illustrate how relatively soft and hard rocks affect drilling rate. The curves were drawn by substituting drill rate and energy values in equation 6. The curves permit the viewing of the specific energy data within the bounds of the finite energy supply for a range of drill rates.

Total drill energy was determined by summing torque, thrust, and water energies for water pressures of 15,000 22,500 and 30,000 lbf/in^2. Drill rates substituted in equation 6 were within the range of values measured during the tests with each stone. More information concerning the construction of curves in figures 11 and 12 is given in appendix D.

Average specific energy values measured during drilling of Berea and Greenwich sandstones (see table 4) are also included on figures 11 and 12. It should be noted that the plotted test values

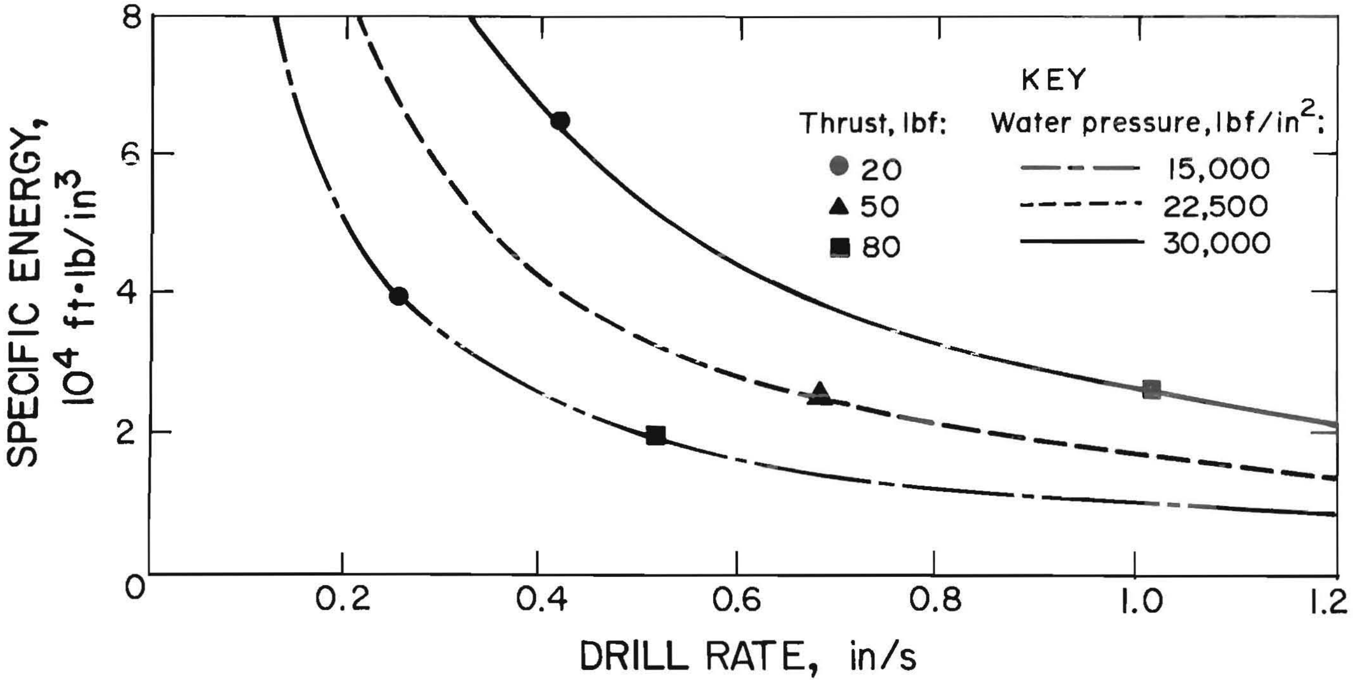

FIGURE 11.–Specific energy curve for Berea sandstone.

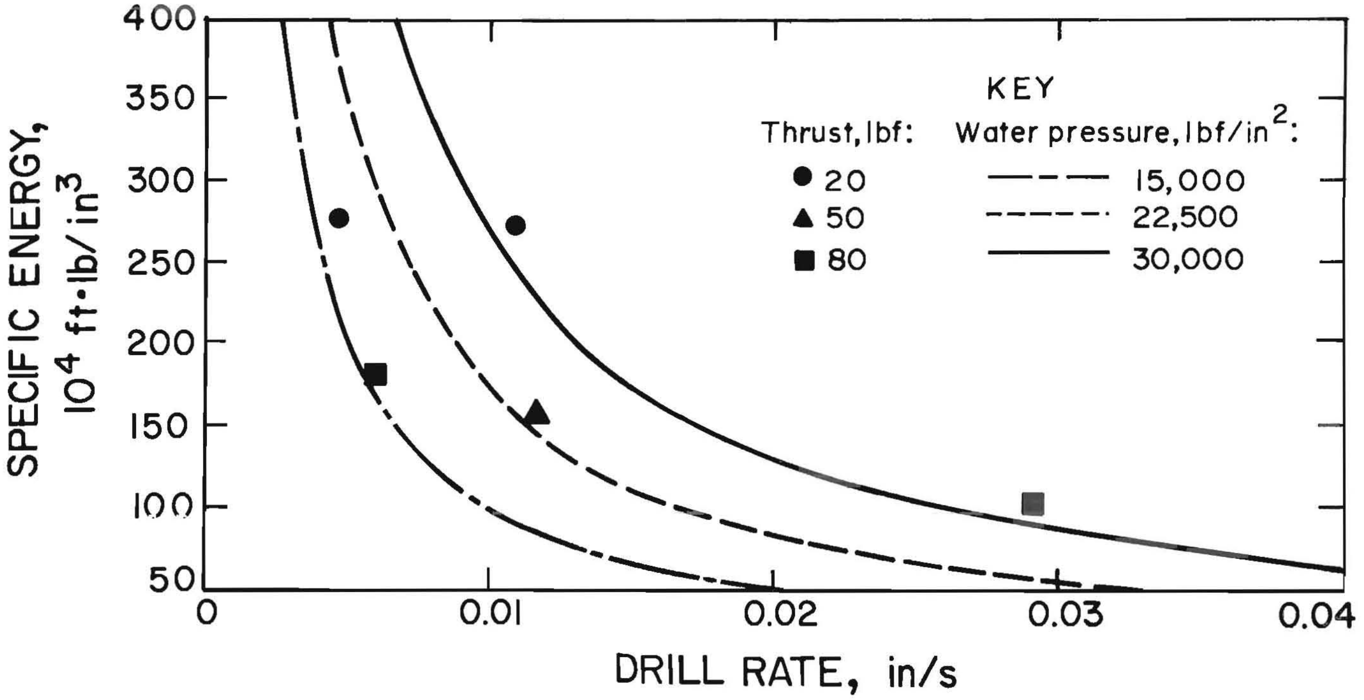

FIGURE 12.–Specific energy curve for Greenwich sandstone.

fall on or near the lines calculated for specific energy. The plotted data illustrate how increasing the thrust at a given water-jet pressure results in reduced specific energy. Similar results were obtained for the other test rocks (see figure 13 and table 4). For Berea and Greenwich sandstones, the reduction in specific energy with increasing thrust diminishes at higher drill rates.

Comparing the plotted data on figures 11 and 12, it can be seen that as the thrust was increased, the magnitude of the change in specific energy was not the same for hard and soft rocks. For example, if the drill thrust was increased from 20 to 80 lbf and the water pressure maintained at 15,000 lbf/in^2, for Berea sandstone, the specific energy was reduced about 19,000 $ft{\cdot}lbf/in^3$. The same increase in drill thrust, while operating at 15,000 lbf/in^2, for Greenwich sandstone resulted in a reduction in specific energy of approximately 1,000,000 $ft{\cdot}lbf/in^3$.

The effect of rock hardness on specific energy can be seen further in figure 13. Log scales were used to plot specific energy versus drill rate for all rocks tested. The graph illustrates the effects of water pressure, drill rate, and rock type on the specific energy for all the samples tested. The harder rock types had lower drill rates and higher specific energies than the softer rocks.

VARIABILITY IN RESULTS

Table 5 gives the average values for the operating parameters used during these tests. The standard deviation is given to compare the variability of the parameters measured. The greatest variability occurred with thrust measurements. This was primarily due to the manual adjustment of the thrust using a visual readout of the thrust level. Due to the heterogeneity of some rock samples, such as coalcrete, more frequent adjustments to the thrust level were required. As a result, the lowest correlation between drill rate and thrust occurred when drilling in coalcrete. The three sandstones, Berea, German, and Greenwich, were more uniform, and the thrust force could be controlled more easily.

Variability in drilling rate while using coalcrete resulted in specific energy measurements that were higher than anticipated. Four additional holes were drilled at thrusts of 30 lbf and water pressures of 15,000 and 30,000 lbf/in^2. Drills rates at 30 lbf thrust were much greater than at 20 lbf. It is believed that an unusually hard aggregate in the coalcrete was encountered while drilling at 20 lbf. The coalcrete results for the 20- and 30-lbf tests were included in the regression analysis. The high standard deviation of the regression (table 3) for coalcrete was the result of combining all coalcrete results.

REACTED TORQUE

The reacted torque at the drill holder is a function of the transfer ratio of the applied torque to the bit, and the

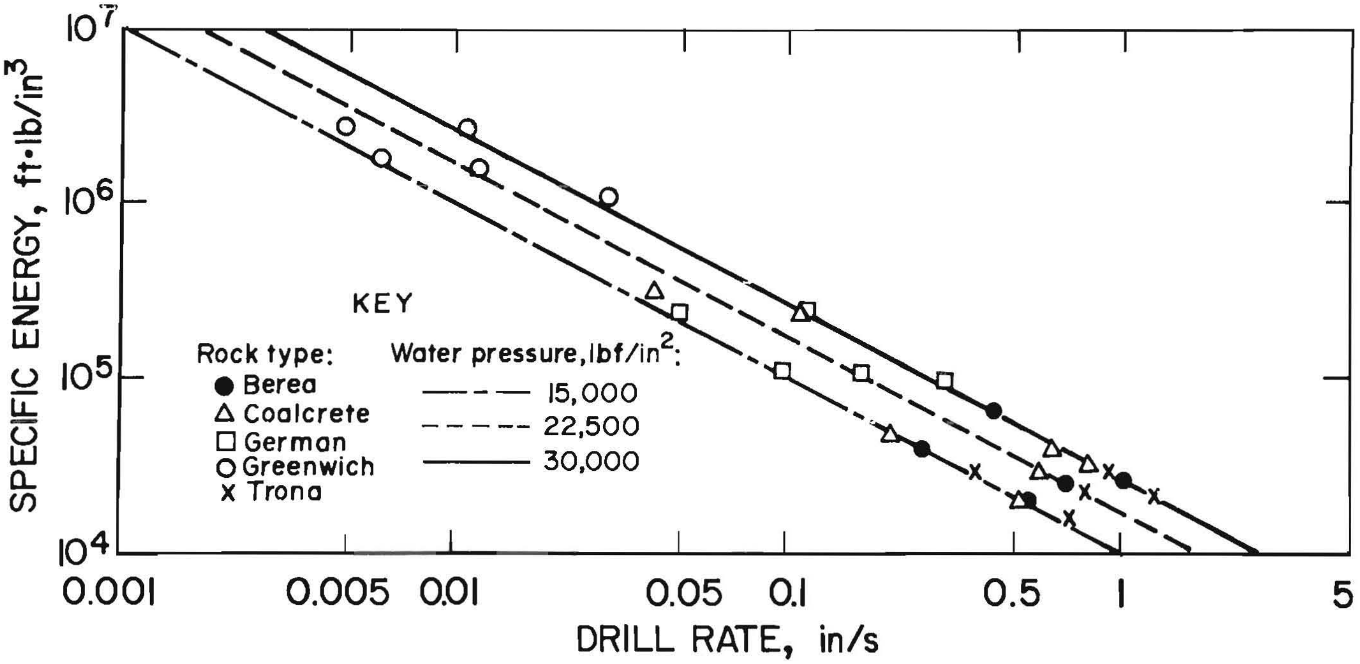

FIGURE 13.–Comparison of specific energy requirements for all rocks.

TABLE 5. - Variation in measured parameters

Parameter	Number of tests	Average	SD
Thrust force, lbf, at--			
20 lbf	20	22.7	3.7
30 lbf	4	31.9	2.2
50 lbf	20	49.8	11.9
80 lbf	20	80.0	12.7
Water pressure, lbf/in^2:			
15,000	22	15,540.0	424.0
22,500	20	23,220.0	581.0
30,000	22	30,609.0	580.0
Water flow, gal/min, at--			
15,000 lbf/in^2	22	1.13	0.04
22,500 lbf/in^2	20	1.42	0.04
30,000 lbf/in^2	22	1.72	0.07
Bit rotational velocity, r/min	64	380.0	10.33
Drill motor:			
Flow gal/min	64	4.36	0.13
Pressure lbf/in^2	64	1,023.0	57.91

SD Standard deviation.

frictional and breaking resistance of the material being drilled. The reacted torque was monitored primarily to obtain information on human factors. If the torque is high, the difficulty of utilizing a handheld drill would increase, and the thrust level that could be applied and maintained in a manual handheld application would decrease.

Using equation 2, the average reacted torque value was determined to be 1.9 ft•lbf, with a standard deviation of 1.8 ft•lbf. This result indicates that reacted torque force would cause no problem for the manual operation of the water-jet-assisted drill. The magnitude of the reacted torque suggests that most drilling was done by the water jets and not the mechanical bit.

BIT WEAR

New bit caps were used for each set of test conditions. The length and diameter of the carbide tip were measured with an optical comparator prior to testing and after completing the test (fig. 14). The decrease in the length and diameter was used as an indicator of drill bit wear. The greatest amount of wear occurred during drilling of the Greenwich sandstone. However, for the amount of drilling performed, bit wear was negligible and not considered to have an effect on the drill rate. Longer testing is necessary to determine long-term wear characteristics and effects.

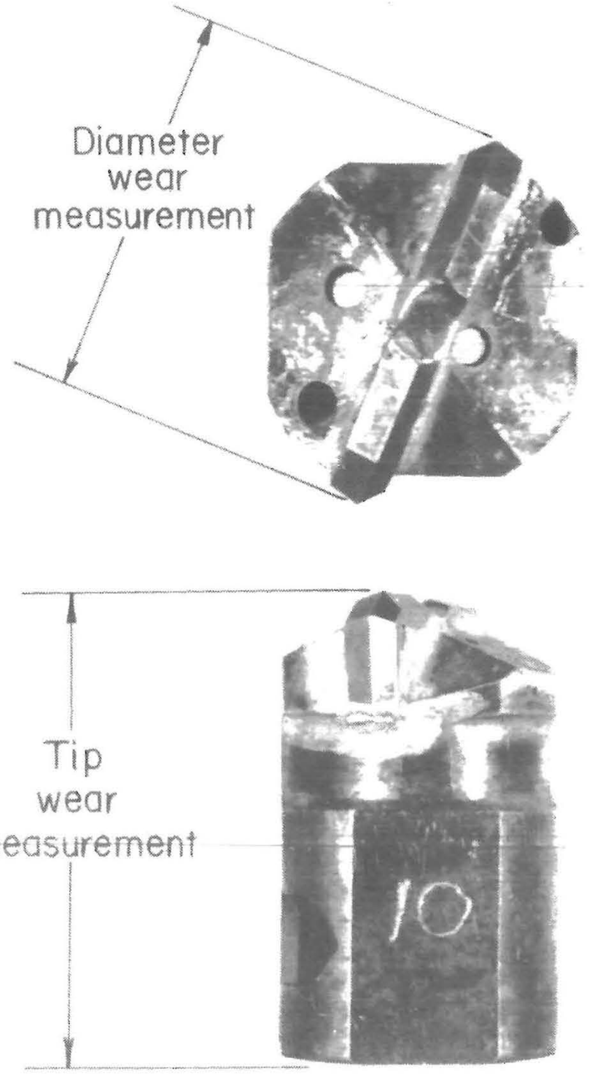

FIGURE 14.—Bit dimensions used to estimate wear.

CONCLUSIONS

The penetration rate for a low-thrust water-jet-assisted drill increases with increasing thrust and water pressure. Rock type is an important factor in determining drilling rate and the specific energy needed to drill the rock. Drill specific energy decreased with increased thrust. With an increase in water-jet pressures, specific energy may either increase or decrease, depending on the rock type. The low reacted torque level would be an advantage when using water-jet assist with a handheld drill.

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APPENDIX A.--PROPERTIES OF THE ROCK SAMPLES

Berea sandstone:

The Berea sandstone was a subgranular quartz grain sandstone with a bulk density of 130 lbf/ft^3 and an unconfined compressive strength of 7,000 to 10,000 lbf/in^2.

Coalcrete:

The coalcrete was mixture of bituminous coal (10 ppv), fly ash (8 ppv), and portland cement (1 ppv), with an average bulk density when cured of 106 lbf/ft^3 and an unconfined compressive strength of 4,000 to 5,000 lbf/in^2.

German sandstone:

The German sandstone was a light gray, fine- to medium-grained quartz sandstone, with an estimated bulk density of 156 lbf/ft^3 and an unconfined compressive strength of 19,000 lbf/in^2.

Greenwich sandstone:

The Greenwich sandstone was a dark gray fine-grained quartz sandstone containing feldspar and argillite, with an estimated bulk density of 163 lbf/ft^3 and an unconfined compressive strength of 22,000 lbf/in^2.

Trona:

The trona, composed of sodium carbonate and sodium bicarbonate, had an estimated bulk density of 134 lbf/ft^3 and an unconfined compressive strength of 6,000 to 10,000 lbf/in^2.

APPENDIX B.--EVALUATION OF THRUST LEVEL APPROPRIATE FOR HANDHELD DRILL

Five subjects were tested for maximum isometric pushing capacity using a force monitor. Two or three trials were performed per subject to insure reproducible maximum voluntary contractions (MVC). The mean MVC for these five subjects was 102.8 lbf (standard deviation = 25.0, range = 80 to 132). Based on the work by Rohmert (7)[1] regarding the ability to sustain muscular contractions, it would be expected that a person could sustain a pushing force without fatigue for a period of 3 min at approximately 25 pct of MVC. This would mean that a reasonable amount of force applied to a drill for this period of time would be approximately 25 lbf. If a 2-min period of exertion was required, 30 pct of MVC (about 30 lbf) could be maintained. For 1 min, 50 lbf, or 50 pct of the MVC, could be applied.

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[1] Underlined numbers in parentheses refer to items in the list of references preceding appendix A.

APPENDIX C.--COMPLETE DATA FOR DRILLING TESTS

Rock type	Thrust, lbf	Water pressure, 10^3 lbf/in^2	Drill rate, in/s	Specific energy, 10^3 ft·lbf/in^3
Berea	52.46	23.5	0.618	27.69
	19.58	15.7	.243	41.16
	69.72	31.0	.965	27.43
	19.99	30.6	.360	71.89
	47.69	23.1	.692	24.33
	74.38	15.7	.518	19.68
	66.68	30.8	1.071	24.73
	82.47	15.5	.519	19.27
	48.42	23.1	.728	23.78
	21.54	15.5	.268	37.51
	51.07	23.3	.694	25.09
	21.29	31.1	.479	57.43
Coalcrete	37.74	22.1	.499	32.74
	65.52	29.4	.607	40.17
	28.97	29.6	.619	40.63
	45.64	22.0	.600	27.27
	33.65	14.8	.175	55.91
	75.46	14.9	.465	21.69
	30.28	30.1	.626	39.61
	51.59	22.5	.583	27.86
	66.35	30.0	.996	25.51
	33.03	14.9	.235	41.03
	92.64	14.9	.527	18.61
	54.74	22.1	.612	26.45
	21.31	14.9	.019	482.65
	25.38	29.7	.108	223.44
	23.26	15.0	.061	153.56
	24.45	30.2	.110	235.78
German	20.88	16.0	.063	163.62
	20.14	30.7	.123	212.16
	48.75	23.5	.165	104.74
	85.10	15.7	.087	120.34
	51.83	23.4	.179	97.98
	77.65	31.6	.313	91.66
	20.75	15.8	.033	306.68
	83.98	31.1	.282	99.41
	48.92	23.7	.170	105.30
	80.22	16.1	.109	115.00
	23.82	30.8	.106	96.80
	48.36	23.8	.158	260.63

APPENDIX C.--COMPLETE DATA FOR DRILLING TESTS--Continued

Rock type	Thrust, lbf	Water pressure, 10^3 lbf/in^2	Drill rate, in/s	Specific energy, 10^3 ft·lbf/in^3
Greenwich............	51.56	23.6	.009	1883.97
	84.81	31.0	.038	762.03
	22.12	30.2	.014	1822.54
	21.87	15.8	.007	1568.17
	80.83	16.0	.005	2112.32
	23.33	30.6	.007	3625.14
	70.74	31.0	.021	1307.46
	22.48	15.7	.003	3991.58
	50.70	23.9	.014	1314.94
	84.95	15.7	.007	1500.71
	50.45	23.7	.011	1710.88
	49.69	23.5	.013	1356.75
Trona................	36.74	31.2	1.092	24.44
	117.80	30.6	1.410	18.57
	94.19	15.8	.854	12.27
	94.18	23.3	.943	18.41
	36.10	23.6	.833	21.60
	22.02	15.7	.409	25.32
	34.18	23.5	.701	26.09
	21.48	31.1	.785	36.17
	20.85	15.9	.335	32.18
	42.56	23.3	.720	25.76
	61.43	31.0	1.152	25.34
	85.79	15.9	.560	19.72

APPENDIX D.--GENERATION OF SPECIFIC ENERGY CURVES

Equation 6, given below, was used to calculate specific energies for the various operating conditions.

$$SE = \frac{T + TQ + W}{\pi * r^2 * D}, \quad \frac{ft \cdot lbf}{in^3} \tag{6}$$

The curves in figures 11, 12, and 13 relate specific energy to drilling rate. Equation 6 was used to generate these curves by substituting power terms for thrust, torque energy, and water energy, and the drill rate (in/s) for the hole depth (D).

The average thrust energy, 49.6 lbf, was multiplied by the average drill rate, 0.4 in/s, to calculate the average thrust power. Although the thrust power ranged from 0.0048 ft•lbf/s to 13.84 ft•lbf/s, the proportion of the thrust power to the total power supplied to the drill was small. Therefore any calculation error due to using the average thrust value was small.

Fluid power from the drill motor and water sprays was calculated by dividing fluid energy (equations 4 and 5) by the time (s) required to drill a hole. The fluid pressure and flow rate to the drill motor did not vary greatly between tests (see table 5). Therefore, the average torque power of 1,430 ft•lbf/s was used for all specific energy calculations. The torque power was approximately 25 pct of the water power supplied at 15,000 lbf/in^2.

For the water pressures used, the calculated power levels were--

15,000 lbf/in^2	5,634.84 ft•lbf/s
22,500 lbf/in^2	10,580.41 ft•lbf/s
30,000 lbf/in^2	15,899.25 ft•lbf/s

The average total power (ft•lbf/s) supplied by the thrust, drill torque, and water jets (table 5) was summed in the numerator of equation 6. The drill rate, x (in/s), was substituted for the length of the drill hole (D). The range of drill rates used to generate the curves was based on the range of drill rates measured during drilling of the rocks (see table 4). For 15,000-lbf/in^2 test, substitution in equation 6 gives

$$SE = \frac{\frac{1.65\ ft \cdot lbf}{s} + \frac{1,430\ ft \cdot lbf}{s} + \frac{5,635\ ft \cdot lbf}{s}}{\pi * \left(\frac{15}{32}\ in\right)^2 * x\ \frac{in}{s}}.$$

The seconds (s) cancel, leaving energy terms in the numerator and volume in the denominator. The specific energy values for 22,500 lbf/in^2 and 30,000 lbf/in^2 can be found by substituting the water power supplied for each water pressure.

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