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Some Basic Aspects of Diamond Drilling

By

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SUMMARY.- A theoretical model of the fracture pattern associated with the penetration of a diamond into brittle rock is presented. Diamond bit design is discussed in terms of this model and the physical properties of the rock. The operating variables associated with diamond drilling are discussed, and some laboratory results are given together with details of instrumentation and methods used to normalize results.

I.- INTRODUCTION

At this date it would be correct to talk about the "state of the art" when discussing the operation of diamond drilling. Very little basic information is available regarding this rather costly operation, and that which can be obtained is rather subjective in nature. The work described in this paper arises from the initial part of a programme of diamond drilling research aimed at obtaining basic data, based upon measurement, from which it is hoped to establish a more scientific understanding of the operation.

II.- THEORETICAL MODEL OF THE CUTTING ACTION OF A DIAMOND BIT

The cutting action of the diamond bit depends upon two basic mechanisms, the axial penetration of the diamond into the material being drilled, and the rotary "shearing" action of the applied torque. These may be modified by the physical properties of the rock.

(a) Axial Penetration

Consider the penetration of a single diamond octahedron into a homogeneous isotropic brittle rock. Fig. 1.

Hoek (Ref. 4) has shown that in a brittle rock under the action of a compressive force, tension cracks develop in the direction of the applied major stress. Thus in Fig. 1 tension cracks would be expected to develop at the apex of the octahedron, and normal to the cleavage face of the diamond. In addition, due to the lateral displacement associated with the wedge penetration, shear stresses and shear cracks develop as illustrated. Penetration would be associated with the initial closing of open "Griffith" cracks followed by elastic deformation up to the point of brittle crack initiation. Plastic yield then occurs as cracks develop (both tensile and shear) until final fracturing develops. Tensile cracks may locate and initiate later shear failure.

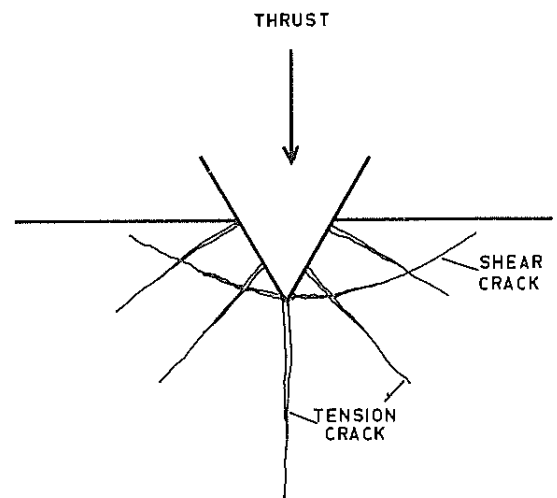


Fig. 1. Penetration of diamond into brittle rock.

(b) Rotational Cutting

In addition to the thrust that results in axial penetration, the diamond is also subjected to a torque which develops a rotary cutting or shearing action. The torque force will cause shearing along the shear cracks illustrated in Fig. 1, while additional shear planes may also be developed. The transition from elastic straining to sudden failure of the rock, under the action of the shearing torque force, accounts for the vibration associated with diamond drilling.

Adjacent diamonds tracking on differing radii tend to develop furrows with intervening ridges. These ridges should shear towards the initial furrow if the diamond spacing and exposure are correctly designed.

(c) Modifications Due to Physical Properties of Rock

Because actual rock types do not conform to the idealized specifications considered in section (a), modifications to the theoretical model can be expected in practice. Such modifications are brought about by variations in the grain size of the constituent minerals and their physical properties, together with the cementing properties of the rock matrices. Some minerals are more easily sheared because they contain pronounced cleavage planes. Where the rock matrix is easily sheared, the properties of the mineral grains may be neglected. Such variations were observed by Pfleider and Blake (Ref. 7) during microscopic examination of diamond drill holes bored in granite, trap rock, taconite, marble, limestone and sandstone.

III.- DIAMOND BIT DESIGN

Based upon the theoretical model outlined in the previous section and the physical properties of diamonds, it is possible to examine some of the basic factors that should be considered in diamond bit design.

(a) Types of Diamond Bits

Two types of diamond bits are in general use, surface set bits and impregnated bits. Surface set bits have diamonds, usually octahedral crystals, set in a metallic matrix on the surface of the diamond crown. Impregnated diamond bits contain very small diamonds or crushed diamond material, sintered throughout the matrix. Diamond salvage is normal with surface set bits but is not practicable with impregnated bits. Impregnated bits are drilled to destruction or loss of gauge.

(b) Diamond Orientation

It is possible with surface set bits to orientate the diamond stones in such a manner as to provide the maximum resistance to wear (Ref. 5 and 8). Barrett (Ref. 1) indicated that oriented impregnated bits had a bit cost of \$0.82 per foot compared with a normal surface set bit cost of \$4.80 per foot. In spite of these claims Marx (Ref. 6, p. 15) states that because of the increased cost in setting the diamonds in the hard vector direction the method has not found wide acceptance.

(c) Diamond Exposure and Size

The exposure of the diamond i.e. the height it protrudes above the surrounding matrix, varies with the size of diamond and the physical properties of the matrix, diamond size and matrix properties being dictated by the nature of the material to be drilled. Marx (Ref. 6, p. 11) indicates that the exposure of the diamond is 1/8 to 1/3 of the diamond diameter with a best tolerance of some 0.001 mm. Considering a bit set with stones 40 per carat, i.e. 1.5 mm nominal diameter, the maximum exposure would be approximately 0.5 mm, and would indicate the maximum

possible size of cuttings.

Surface set diamonds normally vary from 10-125 stones per carat equivalent to nominal diameters in the range of 2.1 - 1.0 mm respectively. Thus the maximum size of cuttings expected would range from 0.7 mm - 0.3 mm approximately. With impregnated bits the cuttings would obviously be much smaller.

(d) Diamond Spacing

There are two measures of diamond spacing, the radial spacing between adjacent rings, and the circumferential spacing between diamonds set at the same radial distance.

Considering the rounded face of a coring bit with equally exposed diamonds, it is evident that one ring of diamonds on the crest would be required to make the pilot cut. The work required to make this pilot cut, and the associated diamond wear, would be greater than that for adjacent cuts, because side shearing into the pilot cut is possible. Thus one would expect a heavy concentration and reduced circumferential spacing for diamonds in the pilot cutting ring. The number of diamonds would depend upon rock to be drilled and the bit life expected.

The radial spacing between diamond rings should be fixed by the width of the ridge of rock that can be side-sheared for a designed diamond penetration. This will obviously vary with rock type and diamond size. The number of diamonds in the ring should be a function of the expected wear life of the bit and the radial distance, since wear is a function of distance travelled.

(e) Matrix Properties

The matrix is designed to hold the diamond firmly in the crown. It is usually specified by its hardness, the following ranges being normal

Standard	Rockwell C	20-30
Hard	Rockwell C	30-40
Extra Hard	Rockwell C	40-50

Marx (Ref. 6, p. 10) states that wear resistance of the matrix is a much more important factor in drilling than hardness, but an acceptable standard is not available. He recommends the standard matrix where erosion is not a problem, the hard matrix for moderate erosion or as an initial choice, and the extra hard matrix in badly broken formations where erosion is severe.

Other desirable properties of the matrix include good heat conductivity, a melting temperature low enough not to affect the diamonds during setting operations, and the capability of being chemically broken down for diamond recovery.

The various matrices tend to be trade secrets formed by powder metallurgical processes. Craelius (Ref. 2, Lecture V, p. 3) indicates that tungsten carbide is generally used as the base metal powder for the matrix, with additives such as cobalt, nickel, beryllium, iron, bronze, copper etc. Custers, Elliot and Young (Ref. 3) describe the various alloys used

and their application.

(f) Waterways

Waterways are provided across the cutting surface of the diamond bit to allow a free flow of drilling fluid. The drilling fluid is necessary to cool the diamonds and matrix and also to remove rock cuttings. The drilling fluid may contain additives such as rock hardness reducers which are designed to break down the intermolecular cohesive bonding in the rock, and thus reduce the specific energy of drilling. Hence the waterways must be designed to give a continuous flow of fluid across the full cutting face of the bit, and at the same time provide a passage for the removal of rock cuttings.

Various waterways have been designed by different bit manufacturers some of which originated from recommendations made by practicing diamond drillers. Some of the factors that influence the number and size of waterways are, the size of diamonds, spacing of the diamonds, the cutting surface area, the designed penetration rate and maximum size of rock particle liberated. These factors together with hole depth and annular area will in turn govern the quantity and pressure of the drilling fluid. It should be noted that the provision of waterways reduces the abrasive erosion of the matrix around the diamonds, and thus may increase bit life where matrix wear is a dominant feature.

IV.- OPERATING VARIABLES IN DIAMOND DRILLING

The operating variables associated with diamond drilling can be divided into two groups; the independent variables and the dependent variables.

(a) Independent Variables

The independent variables are, drilling bit thrust, rotary speed, and drilling fluid flow.

(i) Bit thrust

In section I(a) it was shown that sufficient thrust has to be exerted on each cutting diamond to overcome the yield stress of the rock being drilled.

The total thrust is calculated from the area of contact of the diamonds and the designed penetration of these diamonds. This is not a simple calculation, since the diamonds are not of regular shape and due to wear they do not present a constant area of contact. As wear develops and the diamond faces become rounded it is necessary to increase the thrust to maintain the designed penetration rate. Maximum thrust is limited by a number of factors which include, maximum diamond penetration when the matrix makes contact with solid rock face, the yield stress of the matrix securing the diamonds, and the mechanical strength of the drill stem.

There is also a lower limit of thrust, below which deformation of the rock is purely elastic and fully recovered when the thrust is removed. At thrusts of this order of magnitude polishing of the diamonds and rock take place and no useful penetration or rock removal is achieved.

(ii) Rotary Speed

The penetration rate of a diamond bit is, theoretically, directly proportional to the rotary speed if it is assumed that diamond penetration remains constant. Thus as the speed increases, the quantity of rock cuttings is increased which in turn should require an increased drilling fluid flow rate.

Increasing the rotary speed increases the time-rate of wear since more work is done in a given time. It may not however increase the depth-rate of wear, since there may be an optimum speed at which bit chatter or erosion wear are at a minimum.

(iii) Drilling fluid flow

The drilling fluid flow rate should be a function of the volume of material removed by the bit, and the size of the maximum rock particle liberated. As the penetration rate increases, extra drilling fluid is required to remove the increased volume of rock cuttings and dissipate the increased heat generated.

Drilling fluid flow may also be calculated from the stand point of heat dissipation and cooling of the diamonds and matrix. In this regard Marx (Ref. 6, p. 21) indicates that the amount of fluid required to cool the bit is greater than that required to transport the cuttings in the annulus. Nevertheless, he then calculates the minimum flushing water velocity in the annulus between drill rod and rock, based upon an average rock particle size of 1 mm, to be in the range 0.3-0.6 meters/second.

(b) Dependent Variables

The dependent variables are, penetration rate, torque and drilling fluid pressure.

(i) Penetration rate

The penetration rate is affected by all the independent variables and is additionally affected by the design of the diamond bit and size of diamonds used.

For a constant diamond penetration, the penetration rate will increase with rotary speed. Up to the theoretical limit, when diamond penetration equals diamond exposure, penetration rate increases with thrust. This theoretical limit may never be reached however, due to failure of the matrix or drill rod.

In addition, since it appears that a high percentage of the energy supplied to a diamond bit is consumed in reducing the size of liberated rock cuttings, the more rapidly the cuttings are removed, the smaller the amount of useful energy consumed. Under these conditions more energy is available for cutting which should result in an increased penetration rate. Rock cuttings are removed by the flushing fluid, hence an increase in the flushing fluid flow rate should increase the penetration rate. Sasaki and Yamakado (Ref. 9) found a linear relationship between penetration rate and water flow rate for a diamond coring bit producing a 46 mm core, as the flowrate was increased from 10-20 litres/min.

(ii) Torque

In shallow holes the torque acting upon the diamond bit results from the forces resisting the cutting and grinding action of the diamonds at the rock face. In deep deflected holes additional torque is required to overcome friction between the drill rods and the rock, and also the shearing force between the drill rods and the flushing fluid.

Considering shallow vertical holes, torque should increase with diamond penetration and thrust. Torque would also be expected to reduce with increased water flow rate; because less grinding of liberated particles should take place for a given penetration rate. Sasaki and Yamakado (Ref. 9) found that torque was independent of rotary speed but directly dependent upon thrust.

(iii) Drilling fluid pressure

A pressure difference exists between the fluid descending within the drilling rods and that ascending the annulus outside the rods. This pressure is used to counteract the difference in fluid densities, due to suspended rock particles, and to overcome the frictional resistance to flow.

Increasing the penetration rate, either by increasing the thrust or the rotary speed, will increase the weight of suspended rock particles and hence the differential fluid pressure. However, in shallow laboratory test holes this effect can be neglected.

Measurable fluid pressure differences arise from changes in flow resistance at the bit face. As the diamond penetration increases the flow area at the face is reduced and the flow pressure is increased. This difference is at a theoretical maximum when all the water flows through the waterways. Increasing the flow rate also results in an increase in the pressure difference.

(c) Theoretical Relationships Between Drilling Variables

- Let P = mean penetration of diamonds into rock mass, feet
 R = penetration rate of diamond bit, feet per minute
 T = axial thrust on bit, lbs. force
 F = torque force, lbs. force
 N = rotary speed of bit, r.p.m.
 A = area of hole, square feet
 r = operating radius of torque force, feet
 e = specific energy of drilling ft. lbs. per cubic foot

The specific energy is defined as the work done per cubic foot of material removed.

$$\text{The penetration rate } R = PN \text{ ft. per minute} \quad 1.$$

$$\text{The specific energy} = \frac{2\pi rFN}{RA} + \frac{TR}{RA} \quad 2.$$

Since the second factor of equation 2, which represents the work done by the axial thrust, is found to be less than 1 percent of the first factor, it can be neglected.

$$\text{Thus } e = \frac{2\pi rFN}{RA} \quad 3.$$

For a particular diamond bit $\frac{2\pi r}{A}$ is a constant,

$$\text{so } e = \frac{C_1 FN}{R} \quad 4.$$

If F is found to be directly proportional to T, then for a constant thrust we have

$$e = \frac{C_2 N}{R} \quad 5.$$

where C_2 is a constant.

If e is directly proportional to N, then the penetration rate R must be a constant. If R is directly proportional to N, the specific energy must be constant for the particular thrust.

IV.- SOME RESULTS OF LABORATORY TESTING

(a) Instrumentation

A laboratory diamond drilling test rig has been designed by the author around a two horse power, floor mounted, electric drilling machine. The machine is fitted with a six speed gear box covering the range 140-1,500 revolutions per minute.

The drilling bit is fed by a constant thrust arrangement using a pulley and suspended weight attached to the manual feed shaft. Variable drilling thrusts can be obtained by increasing or decreasing the suspended weights.

The thrust exerted by the drilling bit is measured by a load cell mounted beneath the rotary table which carries the rock specimen. The load cell is a simple fixed-end steel beam with electrical resistance strain gauges mounted on the upper and lower faces to form half of a wheatstone bridge circuit. Thrust is obtained by dead weight calibration.

The torque force developed by the bit while drilling is measured by means of electrical resistance strain gauges mounted upon a cantilever arm. This arm is actuated by a rod fitted to the underside of the rotary table. The table rotates on a tapered thrust bearing which is mounted in a steel shaft that actuates the previously described thrust cell. See Fig. 2. Rock specimens are secured on the rotary table by means of four thumb screws. The rotary table is aligned so that its axis of rotation coincides with the axis of rotation of the drill bit. This device allows the reactional torque force to be measured, as against the difficult problem of measuring the torque in the drill rod. By altering the thickness of the cantilever arm or the radius of the actuating rod, a range of sensitivities can be obtained.

Rotary speed is measured with the aid of a tachogenerator, driven by friction against the knurled collar of the drill feed shaft.

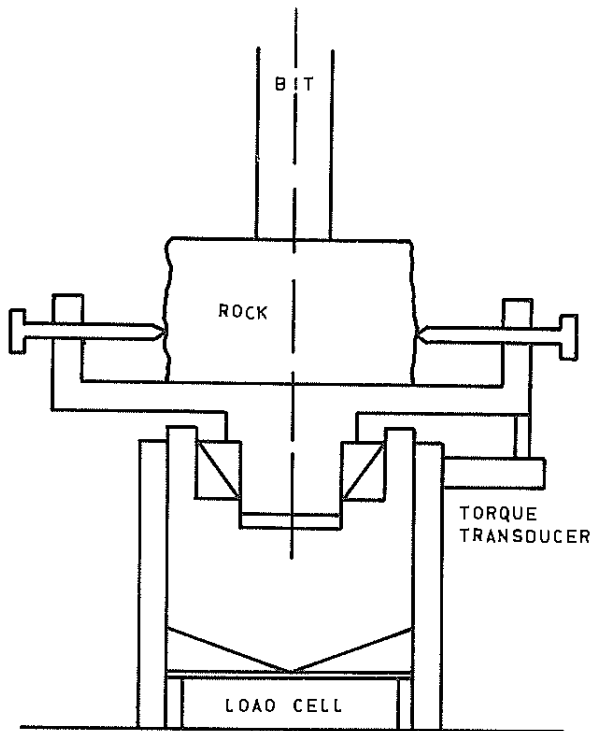


Fig. 2. Diagrammatic illustration showing a section of drill rig.

Bit penetration is measured with an electrical displacement transducer fitted to the rotary swivel which carries the drilling bit.

Drilling fluid flow is obtained from an instrument designed about a mercury manometer which measures the differential pressure associated with the drilling fluid flowing through a restricted pipe. The mercury forms the variable plate of a capacitor which actuates a capacitance bridge as described by (Ref. 10).

The range and sensitivities of the various transducers under operating conditions are tabulated below. Table 1 lists the combined sensitivity of transducer and recorder, i.e. the minimum variation that can be clearly read on the recorder.

In order to make an adequate study of the interrelationships between the drilling variables, it was decided that continuous recording of all measuring transducers was essential. A six pen graphic recorder was chosen in preference to a magnetic tape recorder because of the recording speed range and the ability to visually follow the transducer outputs. Any malfunction of a transducer can be immediately observed and corrective action can be taken. In addition the recording of all variables on one chart greatly simplifies the problems of data correlation,

storage and processing.

TABLE I
COMBINED TRANSDUCER AND RECORDER SENSITIVITY

Variable	Sensitivity	Range
Torque	0.5 lbs.	0-70 lbs.
Thrust	3.5 lbs.	0-450 lbs.
Penetration	0.016 ins.	± 3 ins.
Rotary Speed	10.0 r.p.m.	2,000 r.p.m.
Water Flow	0.0004 gall/min.	0-0.15 gall/min.
	0.003 gall/min.	0-1.0 gall/min.
Water Pressure	0.25 p.s.i.	0-100 p.s.i.

(b) Discussion of Results

The following results were obtained for an EX diamond coring bit cutting a hole of 1.459 inches diameter and yielding a core 0.839 inches diameter. Fig. 3 is a plot of torque force in lbs. against thrust in lbs. The results were obtained from measurements taken in four holes over a depth of approximately 12 inches, at various rotary speeds and thrust. Water flow was maintained constant at 0.124 galls per minute. The plot shows clearly that torque force is proportional to thrust for a given rock/bit combination, irrespective of the rotary speed. The conditions indicated are thus specified by equation 5.

$$e = \frac{C_2 N}{R}$$

5.

Fig. 4 is a plot of penetration rate in inches per minute against rotary speed in revolutions per minute at various thrusts. The figure shows that the penetration rate is proportional to the rotary speed for a constant thrust, and also that the penetration rate increases with thrust. Since the cut area of the hole is 1.119 square inches the range of nominal stresses varies from 160-390 pounds per square inch. Fig. 4 shows that R is proportional to N, which indicates that the specific energy is constant for a given thrust. Fig. 5 shows the relationship between specific energy and thrust. One plot at a constant speed has been reproduced since it was found that above a critical thrust of some 250 lbs., the specific energy did not vary with rotary speed, but was dependant upon thrust alone for a constant rate of drilling fluid flow. A possible explanation of this relationship is as follows. In drilling operations, energy is expended to bring about elastic deformation, plastic deformation and create new surface in the rock. The greater the penetration of the diamonds into the rock, the larger the particles produced, resulting in a reduction in the energy used in creating new surface area; this reduction being independant of the rotary speed of the drill.

Fig. 6 shows this relationship in another form. In this figure specific energy has been plotted against rotary speed at various bit thrusts.

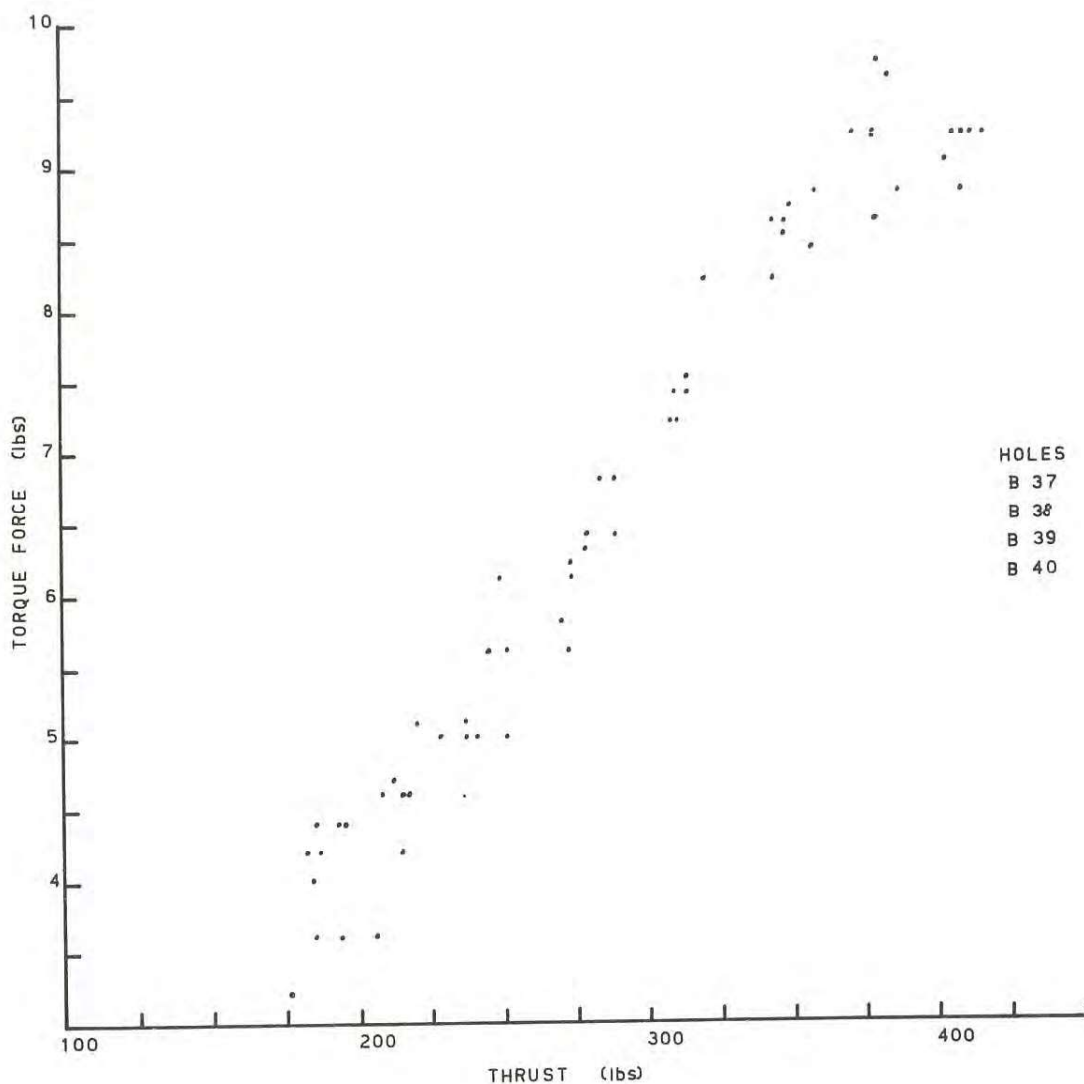


Fig. 3. Torque force and thrust relationships for an E.X. bit.

Considering the higher thrusts, it is seen that specific energy is independent of the rotary speed. As the thrust is reduced the scatter of the measured results increases, particularly at thrusts below 270 lbs. Below this level of thrust the bit is not cutting efficiently, a polishing action is developed with the diamonds removing asperities and creating very fine particles and a large surface area. The large scatter of results may be attributed to loss of bit contact and chatter at the rock surface.

VI.- SOME BASIC PROBLEMS ASSOCIATED WITH DIAMOND DRILLING RESEARCH

Diamond drilling is an expensive operation normally undertaken by relatively small contracting organisations, hence the amount of research that has

been undertaken to study the basic action of the diamond bit is very limited. Some of the results that have been published are of limited application because they have not been normalized to "new-bit" conditions.

(a) Normalizing Drilling Data

When a drilling bit is new the diamonds have the maximum exposure and the minimum bearing area. As drilling proceeds the exposure is reduced due to wear and the bearing area of the diamonds increases. Thus under constant conditions of thrust and rotary speed the penetration rate decreases and the specific energy increases. In compiling data based upon laboratory measurements it becomes essential to take this wear into account and normalize the raw data back to

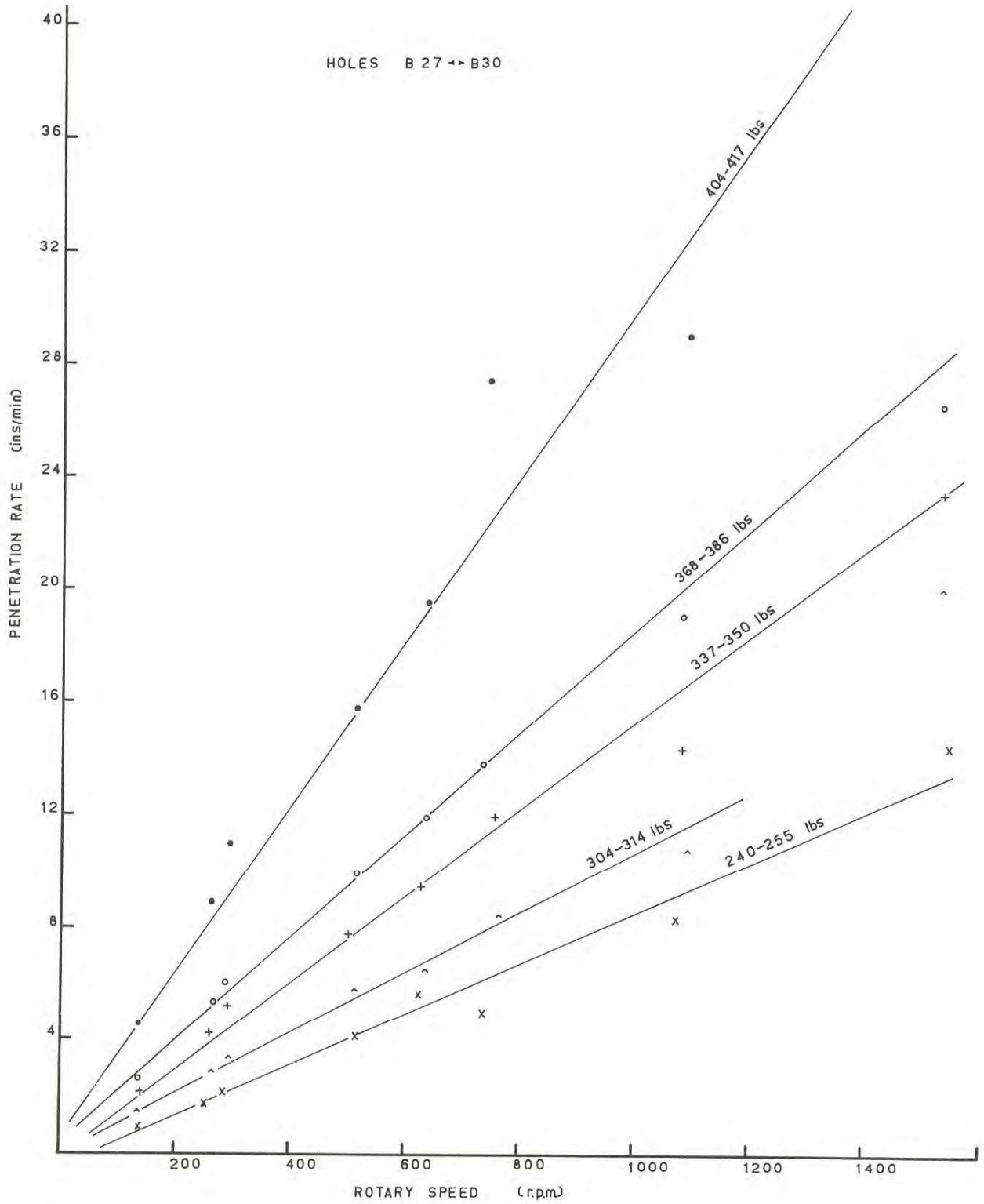


Fig. 4. Relationships between penetration rate and rotary speed of an E.X. bit at various thrusts.

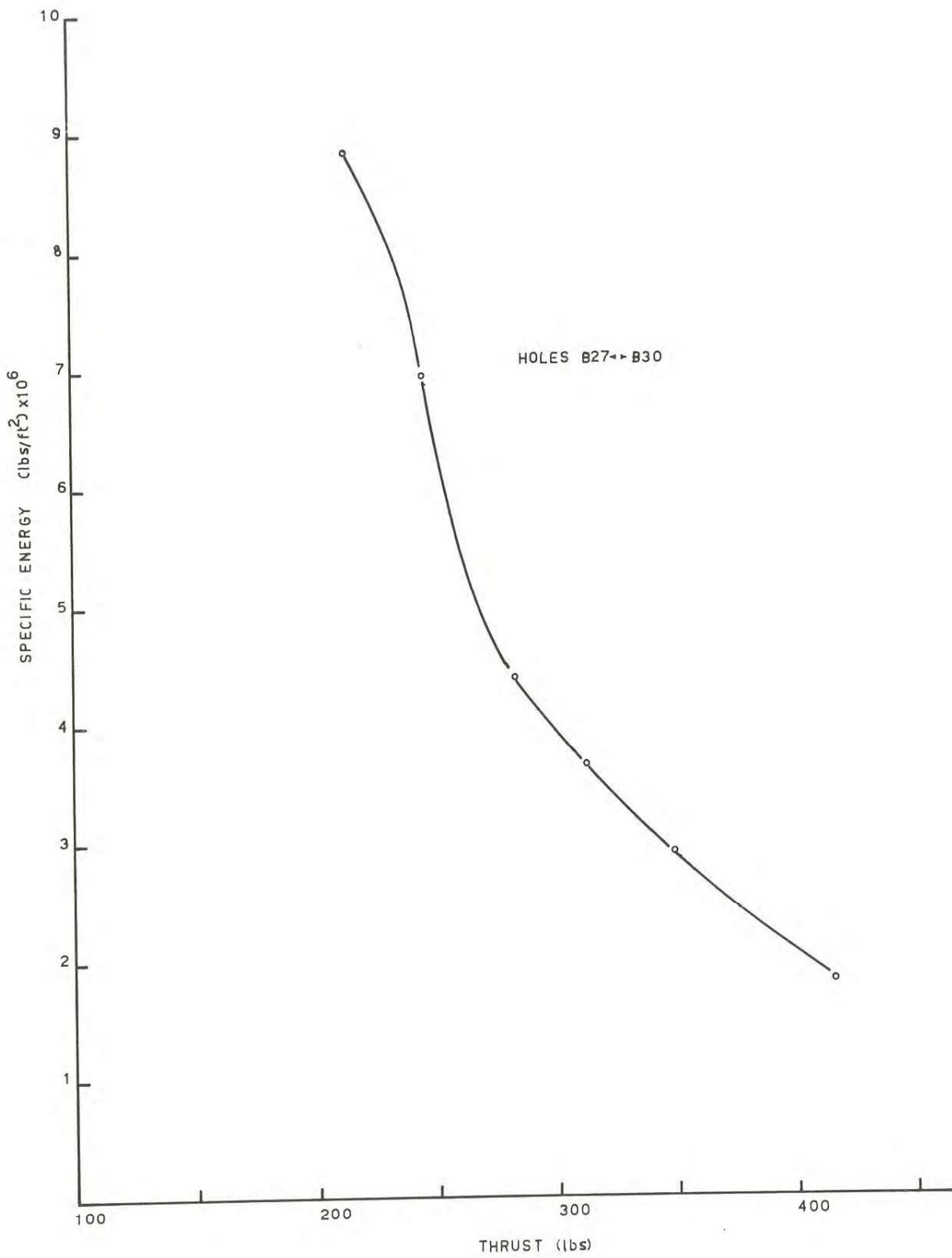


Fig. 5. Specific energy variation with bit thrust, E.X. bit.

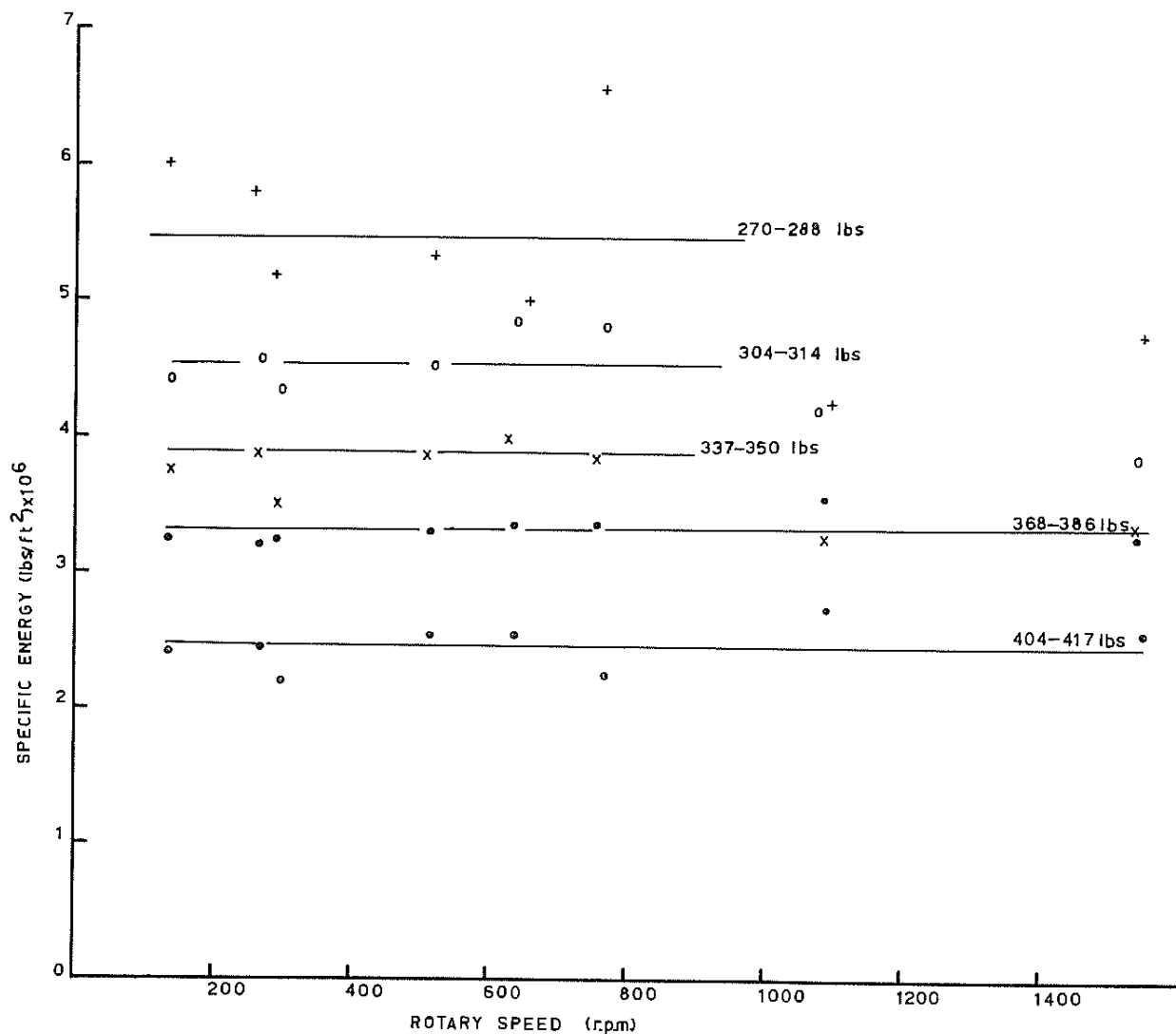


Fig. 6. Relationship between specific energy and rotary speed at various thrust.

"new-bit" conditions.

The data previously presented has been normalized to account for wear, the corrections being made as follows. For each new rock specimen, in which some 10-12 inches of drilling was undertaken, a small depth was drilled at standard conditions of thrust, rotary speed and water flow. The penetration rate and the specific energy for these standard conditions were then tabulated against the cumulative depth drilled. A least squares regression program was executed on the data with the aid of a digital computer to give the best fit relationship. The raw data was then corrected back to "new-bit" conditions by this normalizing curve.

For the data presented the general form of the normalizing curve is given by

$$R = a(\exp)^{-bD} \tag{6}$$

So that $\log R = \log a - bD \log (\exp)$

where R = Penetration Rate (thousandth of an inch/minute)

D = cumulative depth (inches)

a and b are constants; a gives the initial drilling rate, while b depends upon the abrasivity of the rock being drilled.

For the data presented the curve is specified by

$$R = 387.4(\exp)^{-0.0318D}$$

the correlation coefficient of this regression being 0.97419.

It immediately becomes obvious that to justify such a correction procedure for raw data, great care must be exercised to attain standard drilling conditions. The independent variables of thrust, rotary speed and fluid flow must be held constant and in addition the rock being drilled must be homogeneous and isotropic. The rock used in the above tests was a microsyenite obtained from the spillway of the Moogerah Dam near Ipswich, Queensland, its physical properties are as follows:

Compressive Strength	30,000 p.s.i. \pm 5,000
Vickers Hardness	153-169
Shore Hardness	77-100
Grain Size	0.2-2.0 mm.

VII.- CONCLUSIONS

This paper presents a small amount of laboratory measured data in an area where very little factual information is available. Factorially designed tests at higher thrusts and water flows are necessary and are being executed to extend this data. Tests to show the effect of drill fluid flow, rotary speed and thrust upon wear and bit life are essential to indicate optimum drilling conditions. In addition the conflicting claims made regarding surface active hardness reducers need close examination.

VIII.- ACKNOWLEDGEMENTS

The author wishes to thank the Australian Mineral Industries Research Association, the Queensland Mines Department and Universal Carborundum Australia Pty. (formerly Commonwealth Diamond Tools), for their financial support of this research project.

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