1952

# A study of size of diamonds in diamond drilling

Robert J. M. Miller

# A STUDY OF SIZE OF DIAMONDS
# IN DIAMOND DRILLING

BY

ROBERT J. M. MILLER

--------

A

THESIS

submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the work required for the

Degree of

MASTER OF SCIENCE IN MINING ENGINEERING

MINING GEOLOGY OPTION

Rolla, Missouri

1952

-----

Approved by - J. D. Forrester
Professor of Mining Engineering

## ACKNOWLEDGMENTS

The author wishes to acknowledge the help and encouragement given to him by the faculty of Missouri School of Mines and Metallurgy, in particular to Dr. J. D. Forrester for making the research project possible and for critically reading this report.

Particular acknowledgment is due Mr. R. D. Longyear and various members of the staff of the E. J. Longyear Company for suggesting the problem and giving help in various forms.

The Oliver Iron Mining Company generously donated the Rotobore Diamond Drill used in this research.

The Christiansen Diamond Products Company graciously gave technical assistance and financial help in the form of setting the bits used in these experiments.

The author wishes to thank various individuals, some of whom are mentioned in this report, for giving freely of their time and advice.

# CONTENTS

# ILLUSTRATIONS

FIGURE PAGE

FIGURE PAGE

# TABLES

# INTRODUCTION

"A Study of Size of Diamonds in Diamond Drilling" is the research problem which will be discussed in this treatise.

The author's interest in the effect of size of diamonds was created by Mr. R. D. Longyear of the E. J. Longyear Company of Minneapolis, Minnesota. Mr. Longyear, when asked for suggestions for a research problem concerning diamond drilling suggested, among other things, that there was a need for further work on the factor of size of stones. After extensive reading and reviewing, the author learned that many investigators had recognized changes in results attributable to changes in size of stones, but that few had conducted scientific or organized research directed primarily toward analyzing this proposition.

The next step was to determine if the subject were of enough consequence to warrant further study. Correspondence with several manufacturers and investigators stressed the importance and enhanced the interest in the research. It then was decided to pursue this work if the equipment could be obtained.

## REVIEW OF LITERATURE

The trends in the mining industry usually are indicated by the literature published by professional societies, learned institutions, government agencies, trade publications and interested individuals or companies. With diamond drilling, as with many other operations in the industry, much of the pertinent information is withheld from publication because it is thought to be of insufficient importance.

As this was especially true a few years ago, one might consider the designing of a diamond drill bit at that time. One finds that it was ordinarily a matter of using a bit which had been successful on a previous job in similar rock. If the rock had never been encountered before, the bit was designed using the experience of the bit designers as a guide. One of these methods usually worked, but occasionally it did not and a system of cut and try was applied.

Dissemination of knowledge has been more widespread in recent years. There is still some withholding of information, however, because of the presence of competition.

Material written on the size of diamonds as a factor in diamond drilling is ordinarily broad in its scope, but, nevertheless, it denotes the trends. Edson 1/ indicates the size of stones formerly used, " The

1/ Edson, Frank A., Diamond drilling: U.S. Bureau of Mines Bulletin 243, p. 23, 1926.

stones used in metal prospecting ordinarily weigh 3 to 4 carats each; they have ample cutting surfaces and enough body to let them be firmly fastened in the metal of the bit. Stones of this size would not project more than one thirty-second inch beyond the outside of the metal."

Edson 2/ also said, "Black diamonds in their natural forms seldom

2/ Ibid, p. 21

have the size and shape suitable for diamond-drill work, and therefore must be broken before they are marketed....approximately 20 to 25 per cent of the stone is lost in the breaking."

Several years later Storms 3/, among others, recorded a trend in

3/ Storms, W. R., Diamond drill bits and carbon: Engineering and Mining Journal, pp. 96-98, March, 1933.

diamond sizes. "In recent years the trend in diamond drilling has been toward the use of smaller carbon and even scrap carbon."

Later the smaller, non-gem quality bortz and ballas entered the industrial diamond market. There was a considerable difference in the price of the carbon and the bortz.

"Before the war (1917) the price of rough stones in the field was slightly less than $40 per carat....Broken carbon of good quality was selling in 1923 for $100 to $125 per carat...In the fall of 1922 best grade stones retailed at $115 to $135 per carat." 4/

4/ Edson, F. A., op. cit., pp. 21-22.

Long 5/ gave some figures for comparison when he stated the current

5/ Long, Albert E., Effects of core recovery, diamond size and quality on cost of core drilling in gneiss: U. S. Bureau of Mines Report of Investigations 4628, January, 1950.

price of bortz.

"a) AA grade..............current price is $8.50 per carat.

b) A grade..............current price is $5.80 per carat.

c) Congo grade............current price is $4.20 per carat."

It may be seen from these figures why bortz was immediately favored by the industry.

Hopper[6] commented, "Diamonds in sizes from 6 to 12 per carat

---

6/ Hopper, C. H., Diamond core bits at Matachewan Consolidated Mines Ltd., Matachewan, Ontario: Canadian Mining Journal, pp. 600-601, October, 1939.

---

were used by the Matachewan Consolidated Mines Ltd., Matachewan, Ontario, from 1934 to 1937. In 1939 diamonds averaging 20-25 per carat were used......It is evident that the great reduction in cost per foot drilled has been brought about by the introduction of small cheap diamonds by several firms who set stones mechanically. Prior to this a few hand-setters were trying smaller diamonds but the majority would not work with anything smaller than 10-12 per carat. At the present time a number of mines and bit companies are setting by hand, using diamonds 20 to 30 per carat to as small as 60-80 per carat with reported good results."

Price, however, was not the only factor. The diamond drilling companies, when encouraged to use the smaller diamonds because of price, soon found that these diamonds drilled some types of rocks much better than the larger carbons.

Raney[7] said, "The size of diamond used in core bits today is

---

7/ Raney, A. F., Development of modern diamond drill bit: Canadian Mining Journal, pp. 796-803, December, 1940.

---

much smaller than 10 years ago. When carbons were first used it was customary to use large stones weighing as much as 3 to 4 carats each. Later when bortz began to be used the size dropped to stones of 8 to 15 per carat size (about 1/16" in diameter). In the past year the size of diamond has dropped from this figure to 20 to 90 per carat (about 1/40" in diameter). As a result of using smaller stones the number of stones per bit has risen from 4 to 8 for the old carbon stone bits to 60 to 200 for the present day bits."

When carbon was used, the rock was penetrated by a wearing action of the stones. With bortz, however, it was more of a cutting action using less pressure.

Because of their initial cost and operating expense carbons, at present, are not used widely.

Adamson 8/ asserted very clearly some recent opinions on the subject.

---

8/ Adamson, Patrick, What goes on in the diamond drill hole: Engineering and Mining Journal, pp. 70-72, September, 1946.

---

"The quality, size and shape of the diamonds used in diamond drilling have a considerable bearing on the performance of the bit....Pure formation in diamond structure tends to become increasingly rare as the size of diamonds increases. Their efficiency as an abrasive medium, however, runs in proportion to their quality when they are properly applied. Generally speaking, hard, dense formations require small diamonds of good quality, whereas soft, loosely cemented formations can be drilled economically by larger diamonds of somewhat poorer grade. The complete range of rock formations can be drilled with maximum efficiency when the complete range of diamonds, as produced by nature, is available. In practice the range of diamonds available is, for one reason or another, restricted; and this has been one of the factors contributing to slow development."

Adamson 9/ also observed, "An evolution in diamond drill bits has

9/ Adamson, P., Drilling trends; Mining World, Vol. 9, pp. 24-25, March, 1947.

taken place, along with the general improvement of the machines on which they are used. Slow rotational speeds and large stones were used together in earlier days. As machine manufacturers began.......to increase the rotational speeds available, so did the drillers and bit setters begin to change over from carbonados to drill bortz; and it was found the 'smaller stone sizes' using materials of 8 to 10 per carat size, showed increased penetration speed and considerable saving in over all footage cost."

Within the last few years rotational speeds exceeding 12,000 r.p.m. have been tested and bits set with stones of 200 p. c. size have been used on certain formations.

These observations are not being made in the mining industry alone, as may be seen by an editorial in the Petroleum Engineer. 10/ "As in

10/ Anon. How to use diamond bits in deep drilling: Petroleum Engineer, Vol. 19, pp. 179, 182, 184, 186, September, 1948.

conventional diamond drilling it has been found in deep oil field drilling that different sizes and kinds of diamonds, set in various designs are necessary in order to obtain the lowest drilling costs. Diamonds above the range of sizes needed in the mining field are used for this deep hole work."

The preceeding articles illustrate the sizes of stones used and the present trends toward the smaller stones, increased bit pressures and rotational speeds. It is apparent, however, that most of the information was gained from work done in the field. This type of material is of definite value, but many times the strict scientific testing has been sacrificed for additional footage or core. The purpose of most scientific testing in this field has been to improve the bits and drills and to make diamond drilling more useful. Many times impractical methods have been tested and discarded to prove the feasibility of the effective ones.

Some of the field testing apparently has been done under partially controlled conditions as evidenced in an article by Armstrong 11/ in

11/ Armstrong, L. C., Diamond drilling quartz-feldspar intergrowths: Transactions of the American Institute of Mining and Metallurgical Engineers, Vol. 18, p. 1148, November, 1950.

which he advocates using smaller diamonds, "........the thought arises concerning the applicability to the problem of a bit made with very fine grained fragments in a suitable matrix. In using a bit of this type, the difference in relief between hard and soft constituents in the rock being drilled would be almost nil, and furthermore, fresh, angular, diamond pieces would always be available for cutting until the bit was run to destruction."

In the discussion of Mr. Armstrong's paper, Mr. B. J. Westman 12/

12/ Westman, B. J., Discussion-Diamond drilling of a quartz-feldspar intergrowth: Transaction of the American Institute of Mining and Metallurgical Engineers, Vol. 18, p. 1148, November, 1950.

contended, "In general it can be stated that for fine-grained hard rock there are four possible approaches to reduce polish and excessive diamond loss. First is the use of smaller diamonds, second is the use of fewer large diamonds, third is employing the congo diamond, and fourth is the new type of crown design that has 12 to 24 small waterways, depending upon the bit size, and which has had a marked effect on reducing polish apparently by increasing the sludging efficiency which practically eliminates the possibility of regrinding the cuttings."

After considerable testing and evaluation of results on the Mesabi Iron Range, Mr. W. L. Kendrick 13/ advanced these theories, ".....there is

13/ Kendrick, W. L., Drilling and blasting-symposium on handling bulk materials, University of Minnesota, Center of Continuation Studies, p. 8, February, 1942.

a size of diamond or bortz for each kind of ground and the closer the exposed part of the diamond approaches the cuttings that can be torn from the bottom of the hole the more efficient the drilling will be. It can also be put this way: the harder the ground the smaller the diamond.

There are those who believe the answer to this question lies in extremely high speeds but I personally believe 3,000 r.p.m. is the practical maximum for practically all ground. My theory is that instead of whirling a small diamond at high speeds in soft ground, the size of diamond should be increased to cut more from the bottom of the hole per revolution and use lower speeds.......

.....Here are the questions to which the answers must be found for drilling a given rock:

1. Proper size of diamond.

2. Proper hardness of holding medium

3. Proper concentration of diamonds in the face of bit.

4. Proper speed of rotation.

5. Proper pressure on bit.

6. Proper power of driving motor."

## ELEMENTS WHICH MIGHT AFFECT RESULTS

It is necessary, in doing any research, to consider all factors which might affect the results. Listed below are the elements which one must take into account for this particular problem. Varying any one of these would change the conditions of the test and would, therefore, influence the outcome. In order to obtain the desired information, some of the conditions were altered, as discussed below, and the resulting data were obtained.

The author realizes that there are other elements which might be considered but which would probably be of little consequence as far as these tests are concerned. The elements are discussed individually in a general sense and then in their specific application to these tests.

### Driller

The most profound influence on drilling operation and results probably is subjected by the driller himself. On all these tests, the author operated the drill, thus keeping constant the element of the driller.

### Type of Power

Diamond drills may be powered by either an electric motor, compressed air motor, steam engine, gasoline engine, deisel engine, oil motor, or a combination of any of the above. The operation of the drill is somewhat dependent upon the mode of power. For these particular tests an oil motor was used. The oil pressure was obtained from an electrically driven pump.

Type of Feed Mechanism

The feed mechanisms on diamond drills are usually one of two types, hydraulic feed or gear feed. When the gear feed is used, the bit is advanced a certain amount for each rotation; however, the bit pressures may change. With the hydraulic feed, the pressure on the bit is constant at all times; whereas, the rate of advance may change. A hydraulic feed was utilized in these tests.

Physical and Chemical Character of the Rock Being Drilled

When considered from the standpoint of diamond drilling, rocks may vary in several ways: The texture of a rock has a definite effect on drilling speeds; for example, in certain typical rocks individual mineral grains may be oriented in different manners, thus affecting the cutting action of the bit.

Rocks have definite structural features, i. e., faults, joints, and alteration zones will cause the coolant to flow away from the bit, deflect the bit or otherwise affect its operation.

The mineral composition of a rock is an important element in diamond drilling. It has been said that hard minerals fracture or chip, whereas, soft rocks are cut. The rock used in these tests is a dolomite described in Appendix A.

Rock homogeniety is another operating agent. A rock of constant mineral composition throughout will drill much better than a constantly changing one. The rock used in these tests is probably as close to being of constant composition as any readily obtainable one.

The Size of Bits

Diamond bits commonly applied in mining today will make a hole from 1 1/2" (EX) to 3" (NX). However, bits as large as 7 3/4" O.D. and larger are used on occasion. The drilling speed of a diamond bit is inversely proportional to the size of the bit. (EX) bits were used exclusively in these tests.

Under this heading we might consider also the kerf area or area of cut. Wall thicknesses of diamond bits will vary in proportion to their diameter. The relationship between this thickness and the drilling speed is also an inverse relationship.

Shape of the Bit

The bits may have shapes ranging from angular shoulders to round shoulders with semi-circles of varying radii. In the early stage of development bit faces were flat and the shoulders were angular (90°). Of late, the trend has been toward the semi-circular to semi-elliptical type of faces and shoulders. All the bits in these tests had semi-elliptical shoulders and faces.

Rotational Speed of Bit

Rotational speeds commonly used in the past were in the order of 50 to 300 r.p.m. With the advent of new and improved machines and the use of smaller diamonds, the speeds have increased to 3,000 to 6,000 r.p.m. and even experimentally to 12,000 r.p.m. For this research four rotational speeds were used: 1,000; 1,500; 2,000; and 2,500 r.p.m. These speeds were chosen because they were readily attainable on the Rotobore and they gave a good cross-section of speeds used by industry today.

## Bit Pressure

Bit pressures previously employed were generally from 100 to 500 pounds, but new developments have made pressures from 500 to 3,000 pounds more common. The bit pressures used in these tests were: 300; 500; 1,000; and 1,500 pounds. These pressures are representative of those employed in drilling practice today.

## Number of Waterways

Early bits contained no waterways. Later, bits were designed with 2, 4, 6, 8 and more recently with as many as 12 to 24 waterways for drilling shales and other soft rocks. The bits used in these tests had no waterways as the holes were so short that their need was not thought to be important. The greatest depth of horizontal hole was 18".

## Size, Shape and Composition of Waterways

The size, shape and composition generally used for waterways depends on the size of bit and material being drilled. The size may be 3/32" for an EX bit; the shape is generally rounded; the composition of materials may be of the same as the matrix material, or it may be a harder material, such as tungsten carbide.

## Type of Coolant and Sludge Removal Medium

The most common type of coolant and sludge removal medium is clear water. Tests have been run to determine the efficiency of kerosene and salt water as media. These tests have proved clear water to be the best except where there is some other motive in mind, i. e., in cold weather drilling to keep the coolant from freezing. For this research, clear water was used exclusively.

The Amount of Coolant and Sludge Removal Medium

The amount of coolant needed is dependent on several factors, i.e., the type of rock, the rate of advance, the depth of the hole, and the type of bit. One might say that enough water should be used to carry away efficiently the sludge and cool the bit. Four gallons of water per minute were administered in these tests. The water pressure was fairly constant at 40 p.s.i.

Number of Diamonds

The amount of cutting done by a diamond bit will be logically a direct function of the number of stones doing the cutting. Bits having 4 to 20 stones were the common type formerly employed. The number of stones (size 200 p. c.) used recently in bits has increased until now bits may have several hundred stones in each.

Diamond Exposures

The exposure of the diamonds is a direct function of the size, as about 15% of the stones usually are exposed. This figure previously was much higher. The exposures applied in these tests are shown in Table 3. The ideal exposures may be seen in Table 2.

Crystal Shape of the Diamonds

The diamonds may manifest several crystal shapes, i. e., cube, octahedron, rhombic dodechaderon, tris-octahedron, amorphous (Carbonado) or a combination of these. For these tests octahedrons, rhombic dodecahedrons, and tris-octahedrons were the crystals most prevalent. This is further explained under "design of bits".

## Type and Quality of Stones

Stones may be graded by several methods depending upon whom is classifying them. The main consideration is the condition of the stones. The grade symbol is dependent on the dealer's preference. For example, with one dealer, AAA stones are the best grade, whereas, another dealer calls the same grade No. 1. These stones have good crystal shapes, are nearly free from pits and are whole stones. The grade then goes to the AA grade which is somewhat inferior to the AAA grade, but which still consists of good stones. The grading continues in this manner to the poorest stones.

The grade or quality of the stones will be contingent somewhat on the locality from which they originally were obtained. The West African bortz seems to be popular in this country because of its crystal habit and its cost. The petroleum industry is probably the greatest consumer of carbonados today.

For these tests the best grade stones were used, the same grade AAA being employed in all the tests.

## Arrangement of Diamonds

There is usually some difference of opinion as to correct diamond arrangement, although it generally is concluded that the face of the diamond bit must be covered so that each part of the rock being cut must have a diamond pass over it one or more time for each rotation of the bit. As each manufacturer has definite preferences and conducts experiements, there evidentally is considerable room for controlled research on this subject. The arrangement is considered under "design of bits".

Orientation of Diamonds

Several able investigators have done work with the crystallographic orientation of the stones in the bit. It has been concluded that diamonds vary in hardness in the order of 100 to 1 from one direction to another. One can ascertain from this fact that the orientation of the stones would have an enormous effect on the life of the bit. The orientation of stones is discussed under "design of bits".

Uniformity of Diamonds

The more uniform the diamonds are in the bit, the more efficient is the cutting action of each diamond. If the uniformity is not controlled, one diamond is called upon to do more or less than its share. The uniformity of stones is discussed under "design of bits".

Depth of the Hole Being Drilled

As the drilling proceeds to greater depth, more energy intended for the bit is turned into heat through friction of the rods. Because all the holes in these tests were drilled horizontally, and no hole was drilled more than 18" deep, this effect may be disregarded.

Matrix Material

The holding agent for the diamonds may be any one of several kinds. It may be copper, copper-beryllium alloy, copper-nickle alloys of some of the harder compounds like tungsten carbide. The matrix should wear away fast enough to keep the diamonds at the correct exposure. A copper-beryllium alloy was used in these bits to hold the diamonds.

Size of Diamonds

The size of diamonds apparently influences the rate of penetration of a diamond drill bit. This fact has been recognized by several persons (see review of literature). The purpose of this project is to determine the importance in the case of the dolomite in particular, and if possible, in the general case.

DESIGN OF THE BITS

The essence of the problem of size of diamonds rests with the design of the bits as this is the place in which the diamonds are set and from which they do their work. It is important, then, to have them placed in strategic positions so that they will abrade the most rock for the force which is applied to them.

Because of the author's inexperience in diamond drilling, the first step in the design procedure was to investigate literature regarding diamond bits.

The findings are reported in the "review of literature" and in the section "elements which might affect the results". Additional information was secured from Wing G. Agnew, Mont Weather Experiment Station, Bluemont, Virginia and various members of the E. J. Longyear Company, particularly Mr. Stewart Richmond and Mr. Henry Kurtze.

Each of these individuals had very helpful suggestions. Mr. Agnew [14]

---

14/ Agnew, Wing G., Personal communication, January 4, 1951.

---

suggested, "Use a standard type bit set with an adequate number of stones for the diamond size range selected. Use one quality diamond, either AA or AAA grade." This and other advice was followed.

After consideration, deliberation, and consultation the bit design was agreed upon.

The following is a discussion of pertinent bit factors as applied to these tests:

Size of Bits

The size of bit unanimously agreed upon was the EX bit. This bit has the dimensions: 1.460" O.D., and .845" I.D. and it produces a hole 1 1/2" in diameter and a core about 13/16" in diameter depending upon the type of rock being drilled.

The reasons for choosing the EX were: (1) the bit is a size used commercially and the results, therefore, would be of practical value and, (2) the bit is the smallest size used commercially in the United States, thus the cost of the tests would be lower than if a larger size bit containing more diamonds were adopted.

Shape of the Bit Base

A bit face shape was chosen that would work well on the type of rock to be drilled. The semi-rounded bit face called type "W" by the E. J. Longyear Company was selected. The bit shape may be seen in Figures 9 through 28. The wall thickness was 9/32".

Size of Stones

The sizes of stones to be set were decided on as 10, 15, 25, 40, 60, and 100 per carat. These were chosen because they covered the range of sizes used in most diamond drilling today, especially if one considers mechanically set bits.

The author realizes that smaller sizes are used, i.e., 200 per carat, but these would be very difficult to set in the bits without using impregnating processes. If impregnated bits were used, such factors as orientation and exposure could not be controlled easily.

Figures one through six present a picture of the size relationships

Figure 1. Size 10 p.c. diamonds


Figure 2. Size 15 p.c. diamonds

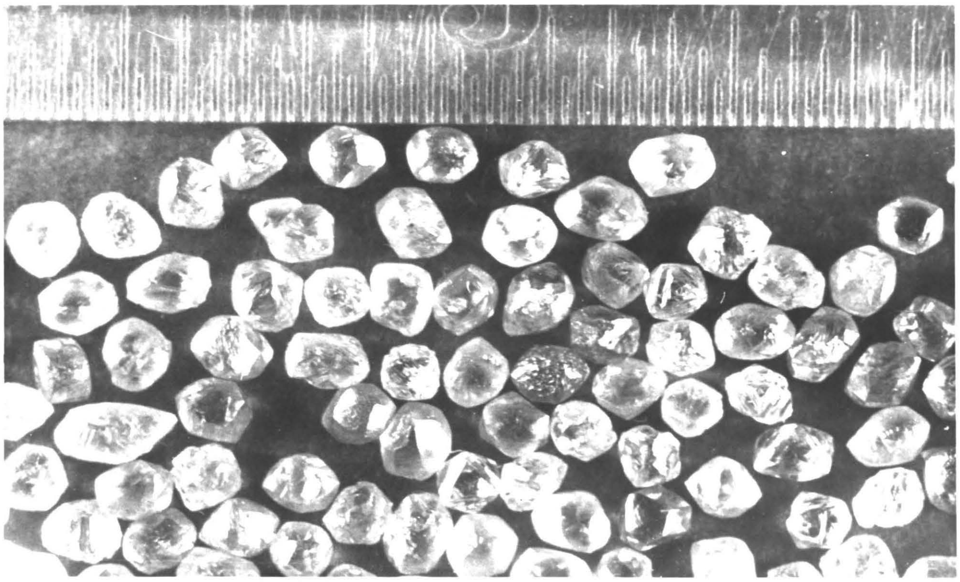

Figure 3. Size 25 p.c. diamonds


Figure 4. Size 40 p.c. diamonds

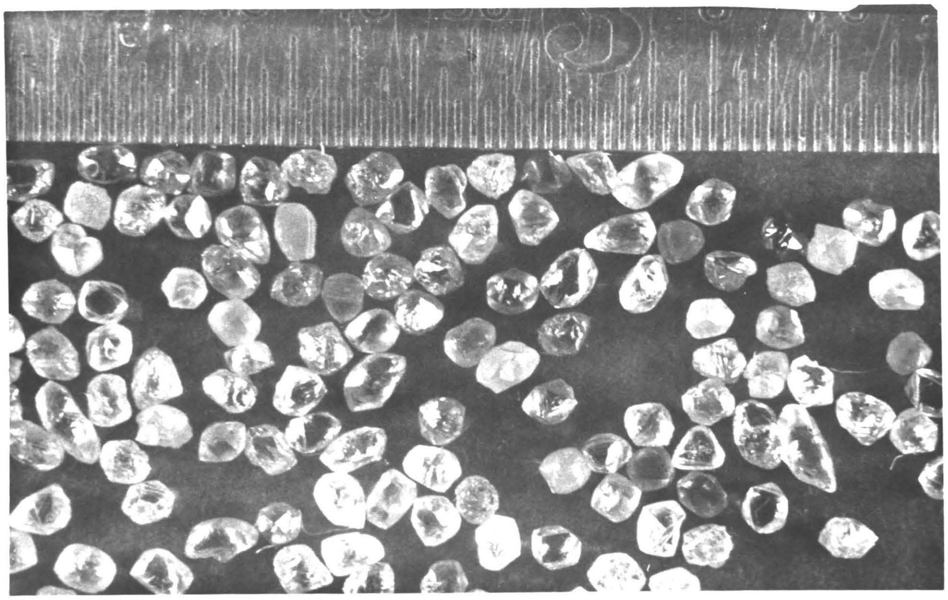

Figure 5. Size 60 p.c. diamonds

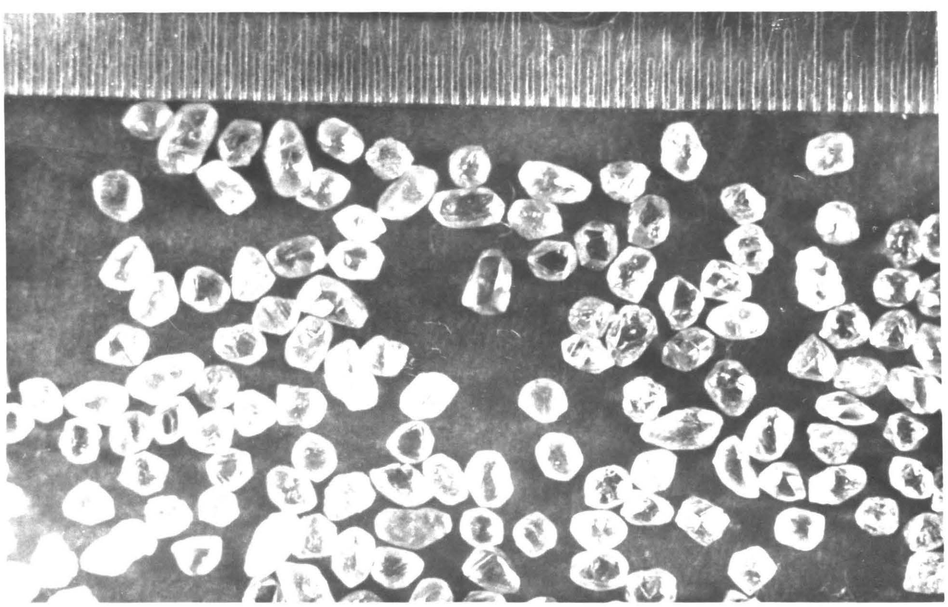

Figure 6. Size 100 p.c. diamonds

of the stones. One can see the size of the stones relative to the rule in the photograph. Each unit on the rule represents 1/64".

Shape and Grade of Stones

The crystal shapes may be seen in Figures one through six. The stones range from euhedral to subhedral to anhedral crystals, the former two types taking the form of octahedron, rhombic dodecahedrons, and tris-octahedrons.

The grade of stones used was no. 1, also called AAA. The E. J. Longyear Company donated 30 carats of each size. The author was permitted to choose the particular stones he wanted.

Choosing the Stones

The stones for the bits were selected in the following manner: (1) The entire 30 carats of each size were placed in a tray under a binocular microscope and the desired crystals were removed to another tray. The diamonds were chosen in the following order of descending desirability: tris-octahedron, dodecahedron, and octahedron--the reasons for which are explained under "orientation of stones". The stones were selected for their euhedral shapes, freedom from fractures, absence of pits and freedom from inclusions. Some of the stones set apart, however, were octahedrons with inclusions of a dark mineral, probably graphite. (2) The preferred stones then were put in a glass tray and immersed in an optical oil of high index of refraction, as near to that of the diamond as possible. The diamonds next were put on the stage of a petrographic microscope and subjected to polarized light. This polarization developed in the stone a play of colors, the order of colors directly proportioned to the degree of internal strain in the crystal. It was assumed that the stones with a higher amount of internal strain would fail before the ones with a lesser amount. The diamonds which were strained the most were rejected and others substituted for them.

It occurred to the author that this type of grading might be applied commercially in selecting good stones.

It appeared that nearly all of the stones were strained to some extent, but some of them were taxed considerably more than others.

One phenomenon particularly impressed the author, the fact that most of the mineral inclusions were parallel to and between the octahedral faces. The author brought this fact to the attention of Mr. John Rosenfeld and Mr. Matt Nackowski of the Geology Department, Missouri School of Mines and Metallurgy. It was decided that this could be expected because there was actually little difference in the molecular structure of the octahedral diamond and the hexagonal graphite crystal. This would account for the straining of the diamond as it changed to graphite while attemtping to reach equilibrium at the earth's surface.

After the stones were chosen, they were sent to Christiansen Diamond Products Company, Salt Lake City, Utah for setting in the bits.

<u>Orientation of Stones</u>

It was decided to orient the stones at random because it would be nearly impossible to set all diamonds oriented in the hard vector directions. If this were possible, it would be time consuming. There is no reason to assume that one size diamond bit would have more or less diamonds oriented in the hard vector directions than any other size, especially if they were implaced by the same setter.

As was mentioned earlier, the stones chosen were tris-octahedrons, dodecahedrons, and octahedrons, in that order of descending desirability. The justification of this method was expressed by Albert E. Long 15/

15/ Long, Albert E., Diamond orientation in diamond bits, procedure and preliminary results: U. S. Bureau of Mines, Report of Investigations 4800 June, 1951.

when he related, "From experience gained in setting the AAA grade stones used in the.....bits, it was found that the crystalline form on the dodecahedral diamonds was such that, if they were set in the random fashion, the chances for their being placed in the bit mold in the hard vector orientations were greater than for any other crystal form except the tris-octahedron. The author has noticed that in West African bortz the percentage of dodecahedral crystals is generally much greater in the high-quality stones. The higher percentage of dodecahedral stones in the higher quality stones may possibly be one of the principal reasons why bits set with high quality stones consistently out perform those set with lower quality stones. Bits random-set with high quality stones out perform those set with lower quality stones because the greater number of dodecahedron-shaped stones increase the chances for a greater percentage of the stones to be set in hard vector directions.

Dr. Slawson contributed the following comment:' It has always been said in the trade that Brazilian stones are harder than African stones. The word Brazilian is most commonly used to describe dodecahedrons and I am sure that only a small percentage of the stones called Brazilian actually came from Brazil. Generally, such a widely held idea has a basis in fact. Drill setters probably observed that the dodecahedrons were superior and, because that Brazilian stones were characteristically dodecahedrons, attributed the hardness to geography rather than crystallography'."

The preceeding statements justify the method of stone selection.

Arrangement of Diamonds in Bits

The employment of the six sizes of stones previously mentioned was agreed upon. The plan was to pick one pattern commonly employed in dolomite using a 40 p.c. bit as a standard and to repeat the pattern more often as the size became smaller and less often as the size became larger. This method would tend to keep the pattern the same and to eliminate one variable, i.e., change in pattern.

After consulting with Mr. Max Jenkins of Christiansen Diamond Products Company, it was ascertained that the face would not get complete coverage in the 100 p.c. size if the 40 p.c. were used as the standard. In addition, there would be overlapping in the 10 p.c. sizes.

The conclusion reached was that two bit patterns would be employed better as originals. The 15 p.c. bit was chosen as a standard using four stones to cover the kerf width (Fig. 7). The 10 p.c. and 25 p.c. conformed to the 15 p.c. prototype. The 60 p.c. bit was picked as the other bit with five stones to cover the kerf area (Fig. 8). The 40 and 100 p.c. bits also have the five stone coverage.

Theoretically, other than having a different size and number of diamonds, these bits would be exactly alike. This series of six bits was called Series A. It was possible to test the effedt of the size of diamonds with these bits.

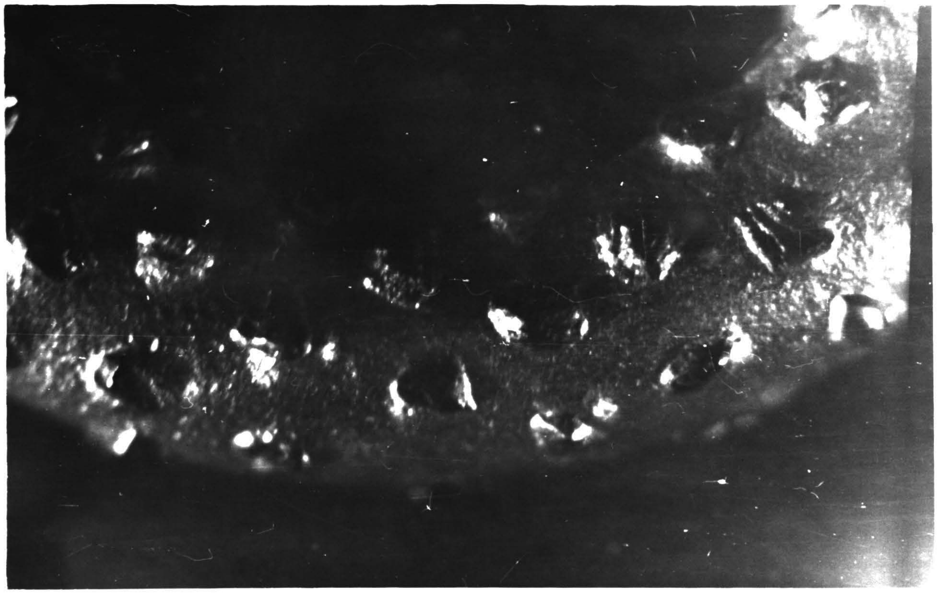

Figure 7. Four-diamond coverage of bit face.

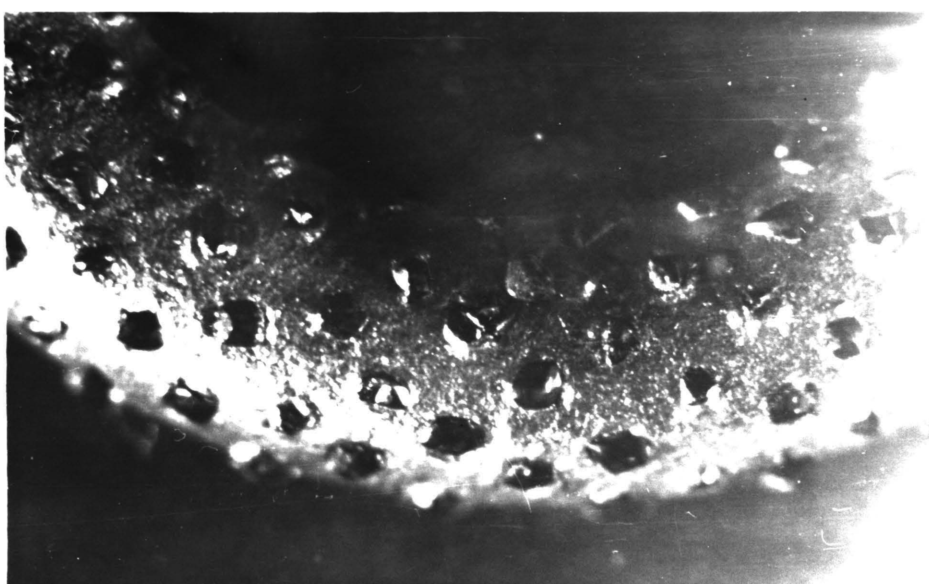

Figure 8. Five-diamond coverage of bit face.

The thought occurred to the author that one bit set with more and smaller diamonds might drill better than a bit set with fewer and larger diamonds merely because there were more cutting points.

To test this problem it was decided to make different bits from the same molds, varying only the size of diamond and the exposure. A comparison between the different bit tests would actually show if there were a definite effect due to a change in size of diamonds. Bits were made with stones of sizes 10, p.c. and 25 p.c. in the 15 p.c. mold. Bits were made also with stones of sizes 40 p.c. and 100 p.c. in the 60 p.c. mold. These bits were called Series B. These ideas are clarified by Table 1 in which the stones and sizes are listed, and also by Figures 9 through 28 where illustrations of the diamond bits are shown.

Table 1

| Size | Series A | | Series B | |
|---|---|---|---|---|
| | Stones | Carats | Stones | Carats |
| 10 p.c. | 96 | 13.14 | 120 | 16.55 |
| 15 p.c. | 120 | 10.01 | | |
| 25 p.c. | 144 | 8.19 | 120 | 6.96 |
| 40 p.c. | 196 | 6.03 | 224 | 6.90 |
| 60 p.c. | 224 | 5.33 | | |
| 100 p.c. | 252 | 4.43 | 224 | 3.82 |

Exposure

In referring to the size of stones in a diamond bit, one actually is discussing the part of the diamond exposed. The protruding portion, of course, is the part which does the cutting.

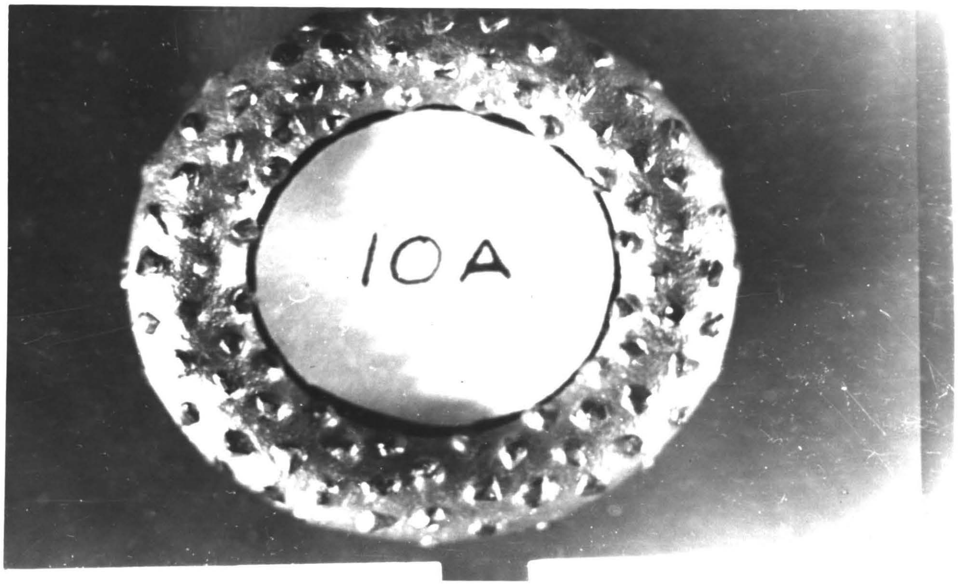


Figure 9. Bit 10a before drilling.

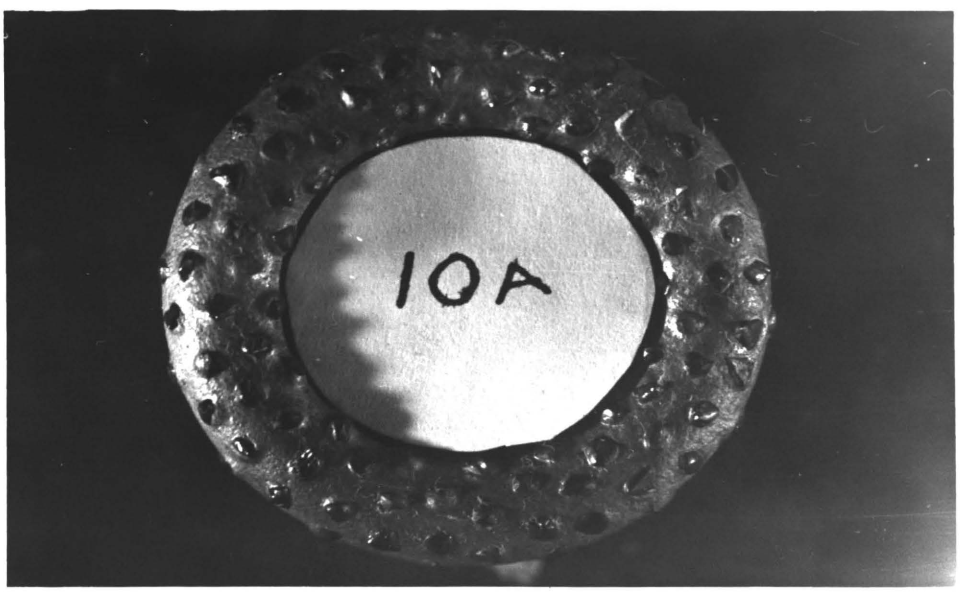


Figure 10. Bit 10a after drilling.

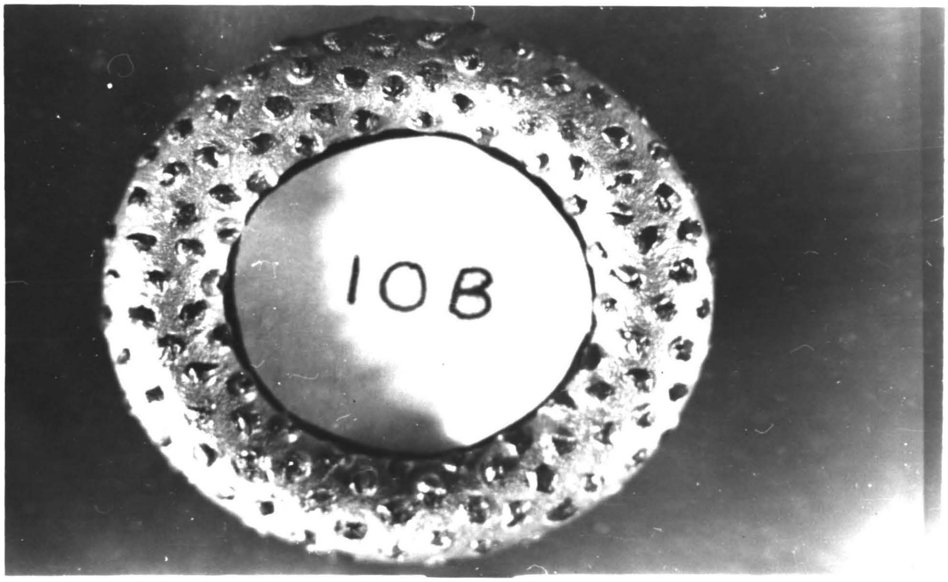


Figure 11. Bit 10b before drilling.

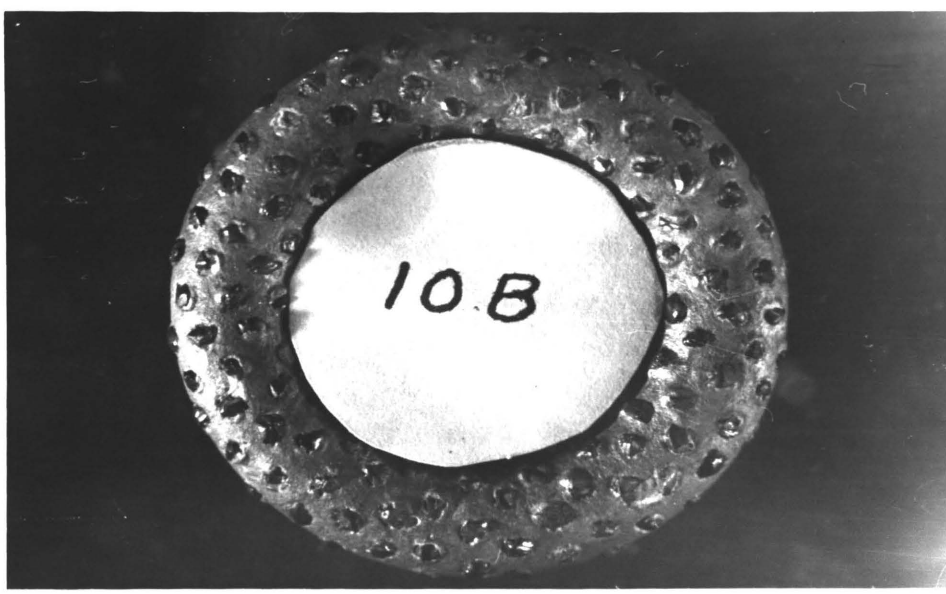


Figure 12. Bit 10b after drilling.

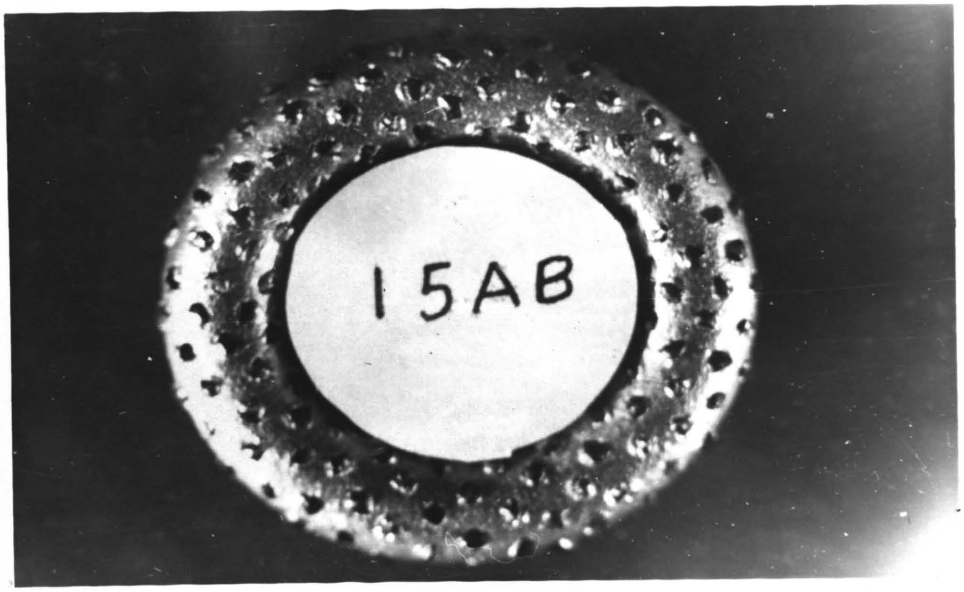


Figure 13. Bit 15ab before drilling.

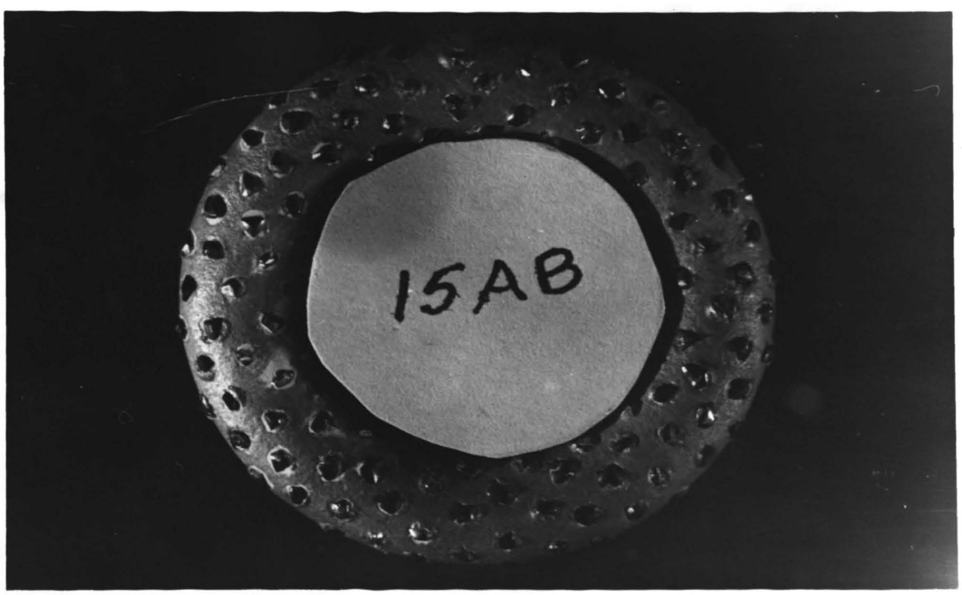


Figure 14. Bit 15ab after drilling.

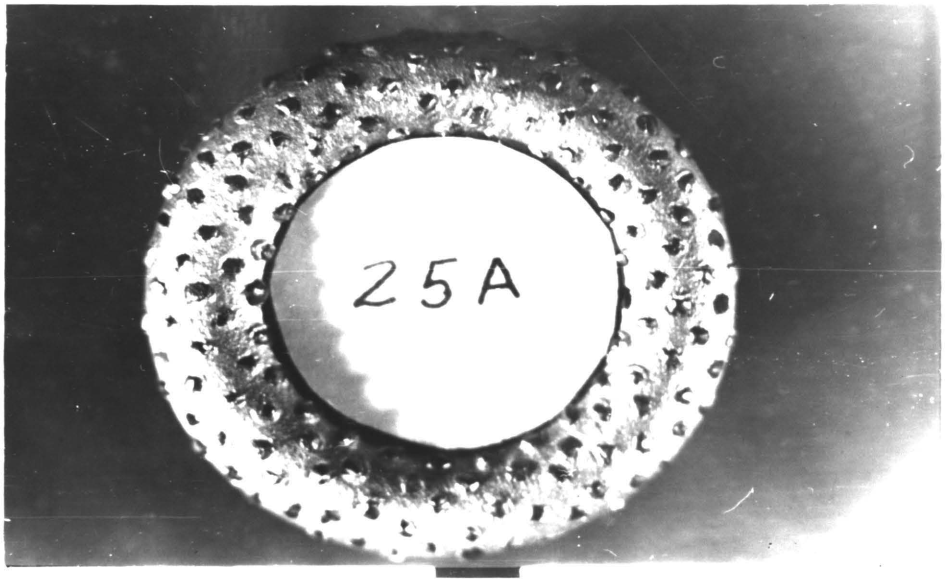


Figure 15. Bit 25a before drilling.


Figure 16. Bit 25a after drilling.

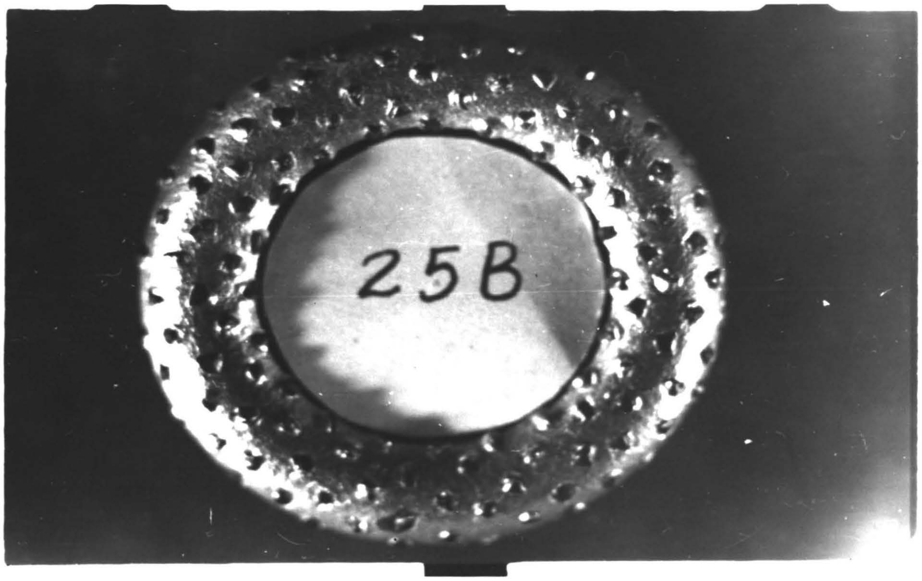


Figure 17. Bit 25b before drilling.

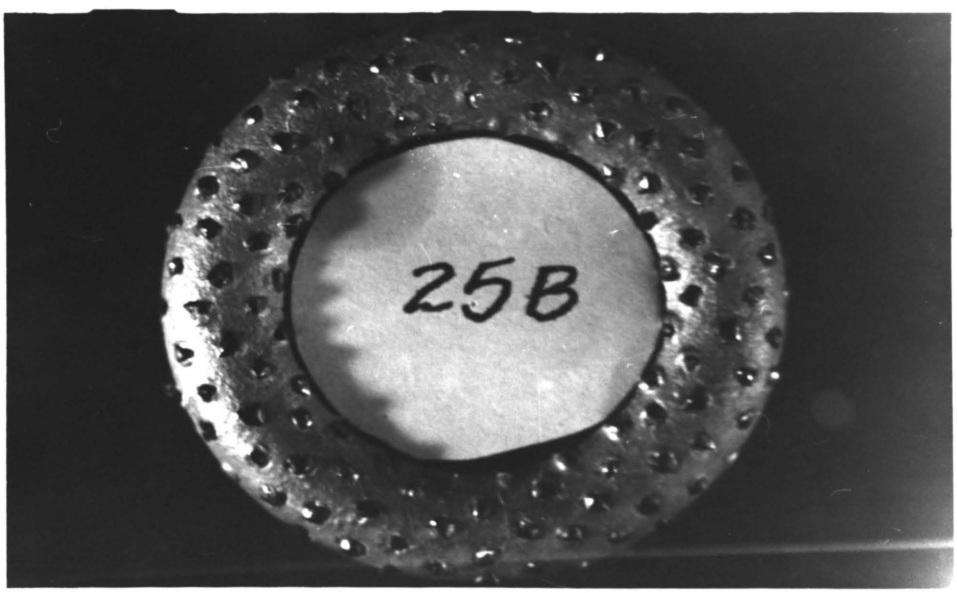


Figure 18. Bit 25b after drilling.

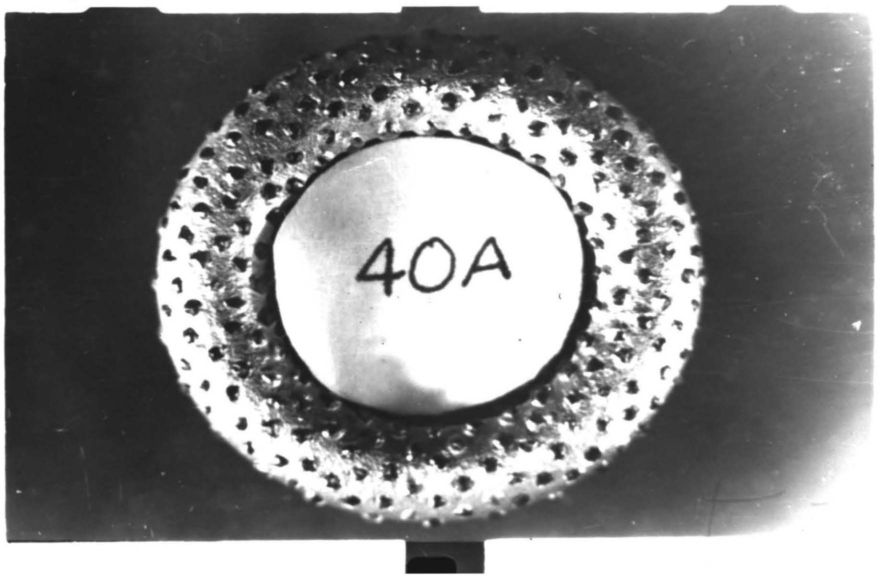


Figure 19. Bit 40a before drilling.

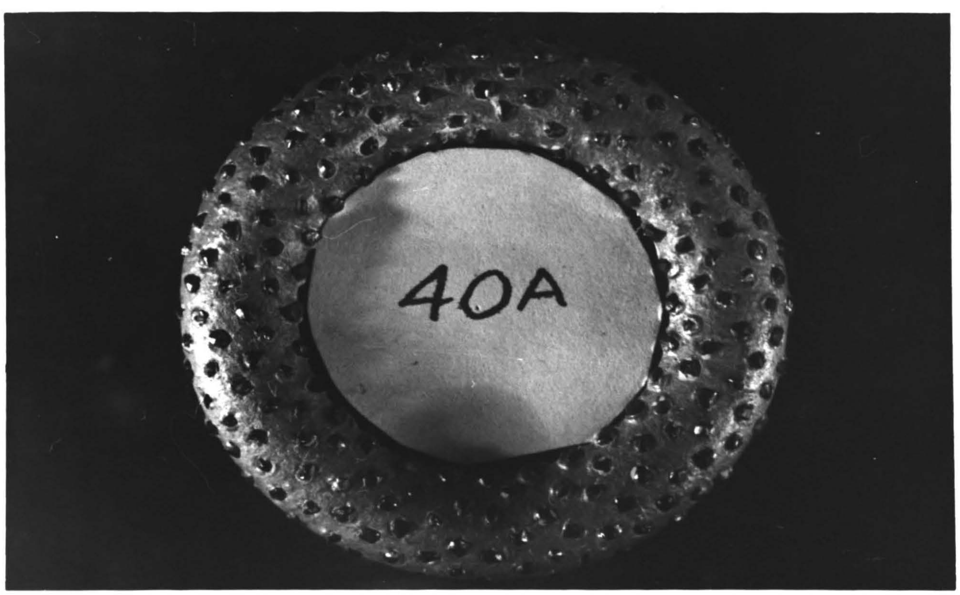


Figure 20. Bit 40a after drilling.

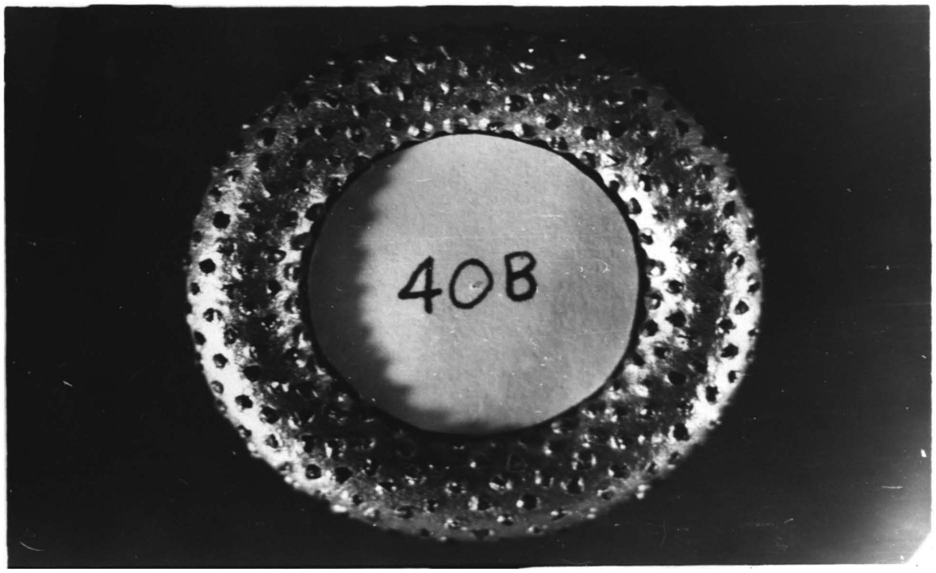


Figure 21. Bit 40b before drilling.


Figure 22. Bit 40b after drilling.

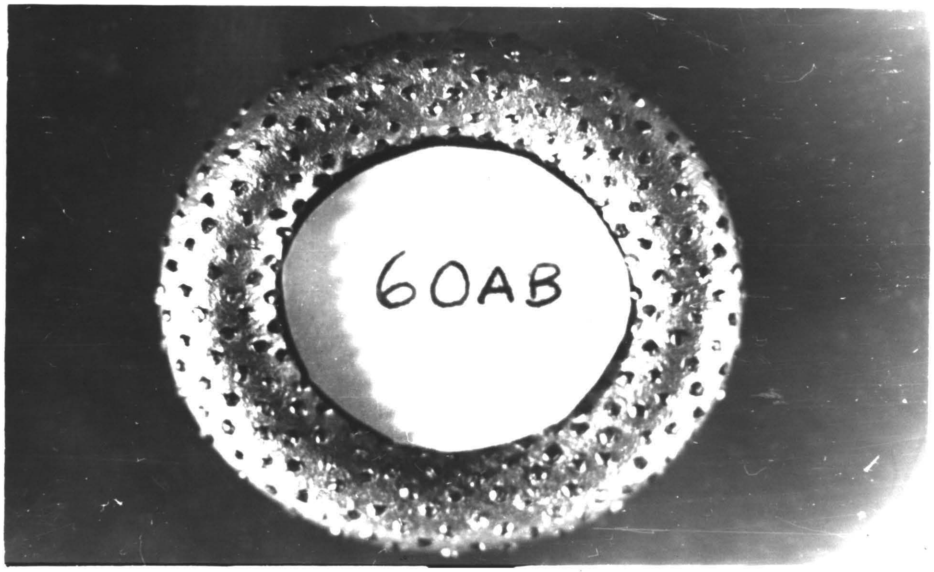


Figure 23. Bit 60ab before drilling.

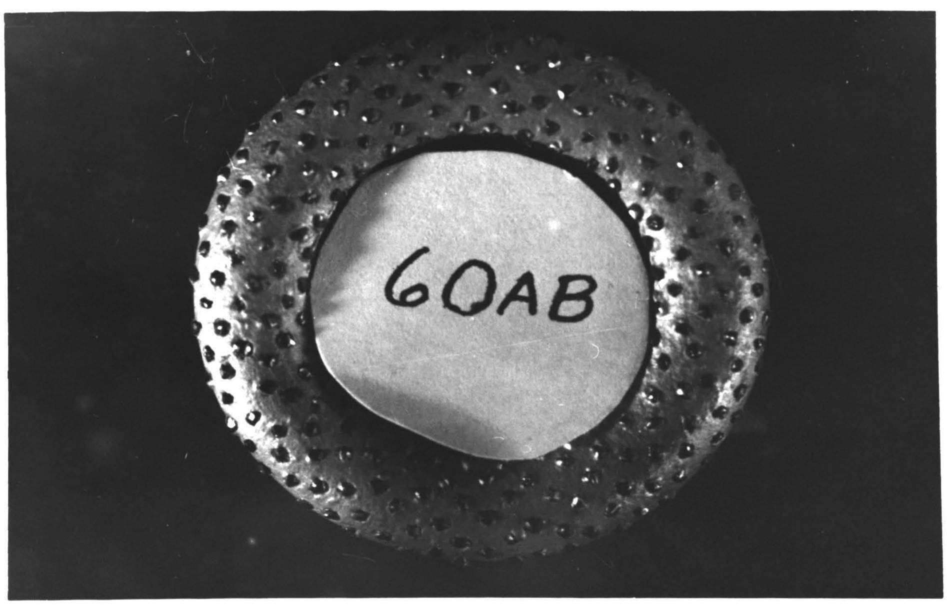


Figure 24. Bit 60ab after drilling.

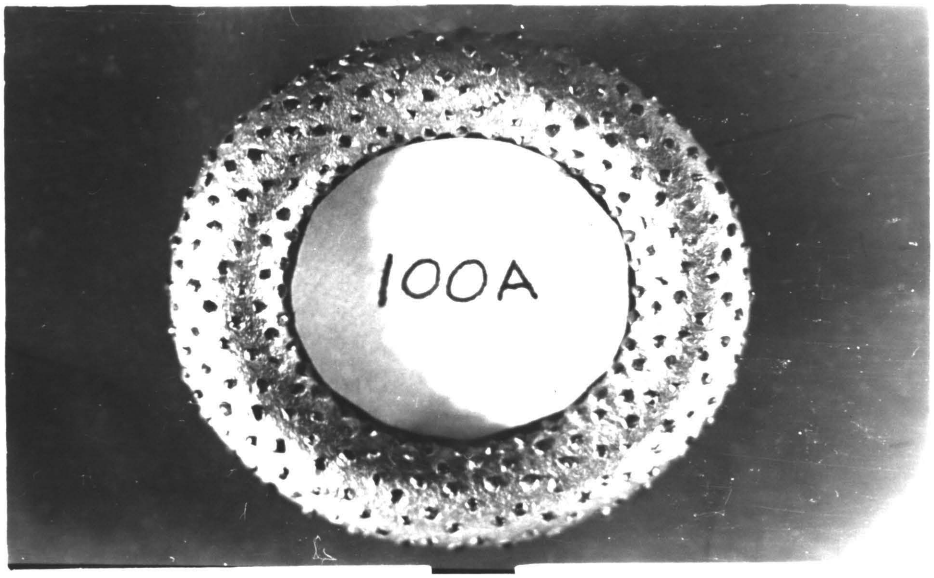


Figure 25. Bit 100a before drilling.

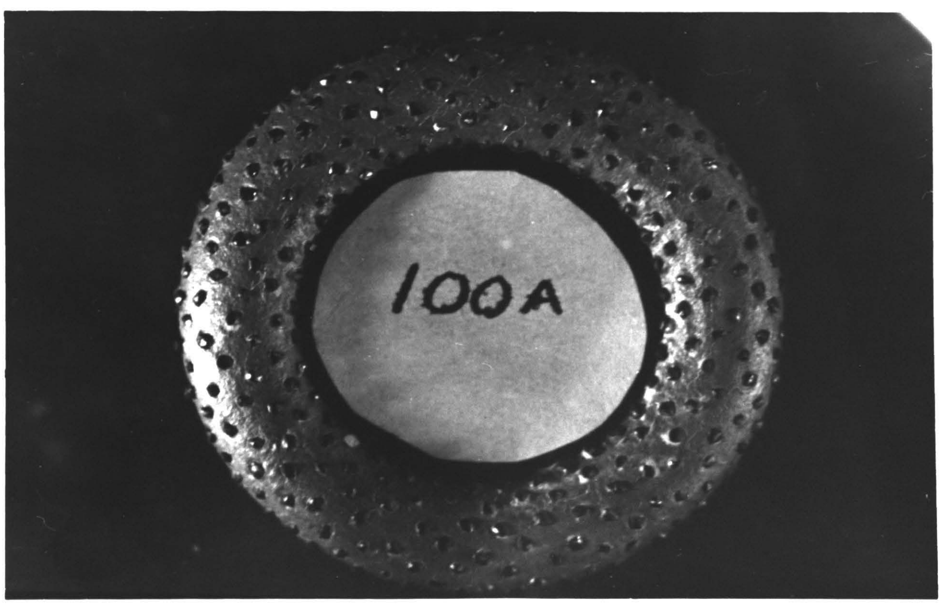


Figure 26. Bit 100a after drilling.

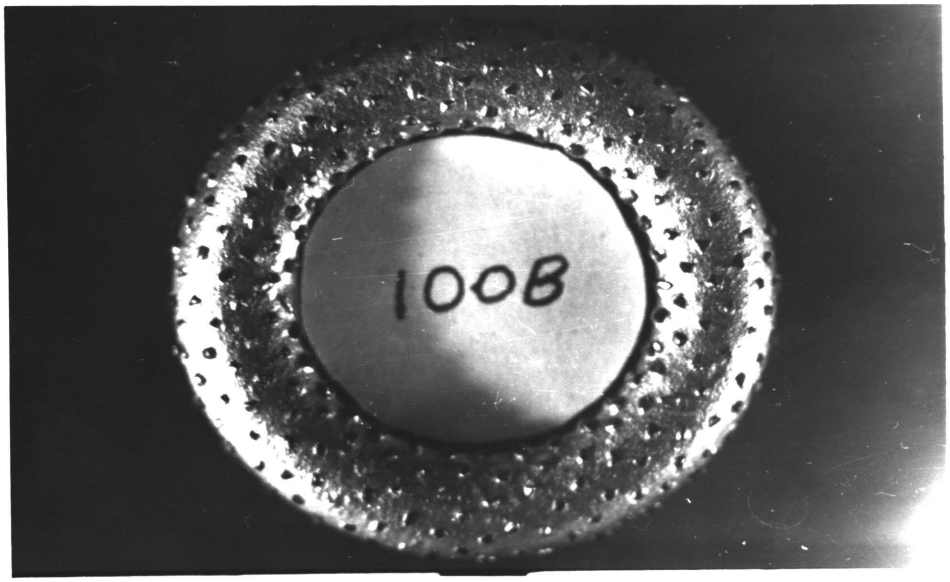


Figure 27. Bit 100b before drilling.

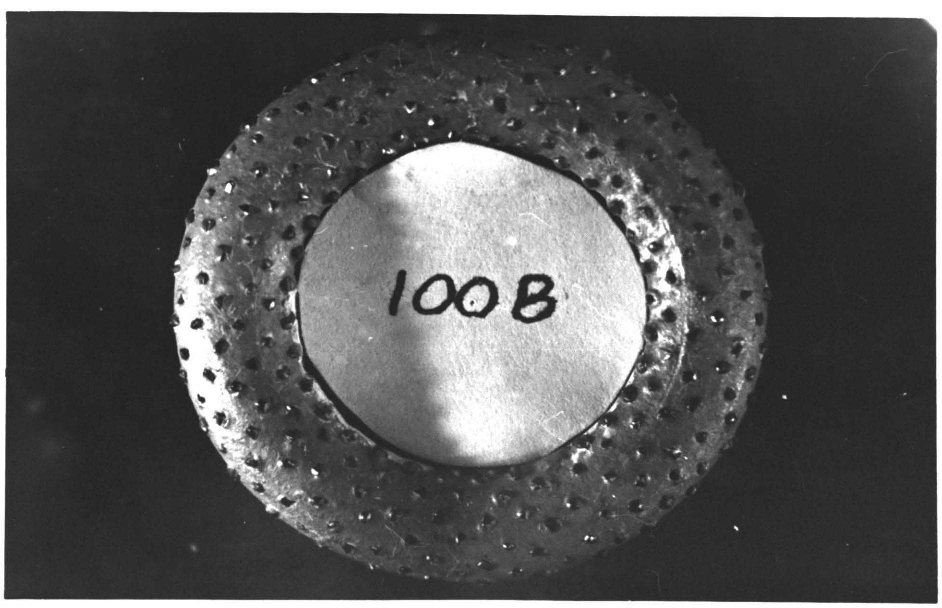


Figure 28. Bit 100b after drilling.

The necessity of having the exposure in a definite ratio to the size of the diamond would seem important. One might conceive of a case in which a 25p.c. diamond exposed .015 inches might cut nearly as much as a 10 p.c. stone exposed the same amount.

Exposures in Table 2 were computed from the theoretical size of each diamond. At that time the size 20 and 75 p.c. were to be used. These sizes later were changed to 15 and 25 p. c. as shown in Table 3.

Table 2

| Diamonds Per Carat | Diamond Diameter in Inches | Exposure (14%) in Inches |
|---|---|---|
| 10 | .0906 | .01270 |
| 20 | .0709 | .00991 |
| 40 | .0551 | .00770 |
| 60 | .0492 | .00686 |
| 75 | .0473 | .00661 |
| 100 | .0453 | .00634 |

The 14% exposure in Table 2 has been arrived at from practice.

Mr. E. M. Jenkins explained that the exposures listed in Table 2 were too precise or fine to be set, thus it was resolved to settle for the exposures listed in Table 3.

Table 3

| Diamonds Per Carat | Exposure in Inches |
|---|---|
| 10 | .015 |
| 15 | .015 |
| 25 | .010 |
| 40 | .010 |
| 60 | .005 |
| 100 | .005 |

Waterways

Bits with two waterways were chosen first, but later this plan was discarded. The reason for this change was that the inclusion of waterways would introduce an additional factor to be considered, namely, "What size of waterways is best?" The author's conception agreed with Mr. Jenkins 16/ who said, "Further discussion regarding the effect of

16/ Jenkins, Edward M., Personal communication, December 19, 1951.

waterways on your test has more firmly convinced us that inclusion of waterways would introduce an additional factor. It is our opinion that for the footage which will probably be drilled no advantage will accure from the use of waterways."

Reaming Shells

The conclusion was reached that owing to the short length of the holes, reaming shells set with diamonds would not be needed. The purpose of the diamond set shells is to keep gauge in the hole, but as mentioned above, this does not apply to short holes. Blank reaming shells, however, were used to protect the rods and bits from excessive vibration.

# THE ROTOBORE DRILL AND SET-UP

The Longyear Rotobore Fh-2 drill shown in Figures 29 through 32 was donated to the Department of Mining Engineering by the Oliver Iron Mining Company. A description of the drill is as follows:

Motor

The motor is a variable displacement type oil motor developing 7.5 horsepower at 1500 pounds per square inch oil pressure and allowing a stepless variation in speeds from 800 revolutions per minute to 2800 revolutions per minute. Rotation of the motor is started by closing the by-pass valve (a) connecting the outlet and inlet piping in back of the motor. Rotation is stopped by opening the valve. The oil motor is activated by oil coming from an oil pump (j). Figure 7 shows this pump (j) along with the other pump (k) that supplies oil for the hydraulic feed. Both pumps are driven by a 15 horsepower, alternating-current motor.

Drive

The rotation and power of the motor is transmitted through a roller chain coupling to the drive shaft. Drill rods are connected to the chuck on the front part of the drive shaft.

Water Swivel

The swivel is located in the drill housing at the middle of the drive shaft. The water enters the drill rods through the chuck, circulates down the rods, cools and lubricates the bit, and carries away the bit cuttings. The amount of water is controlled by a gate valve (b).

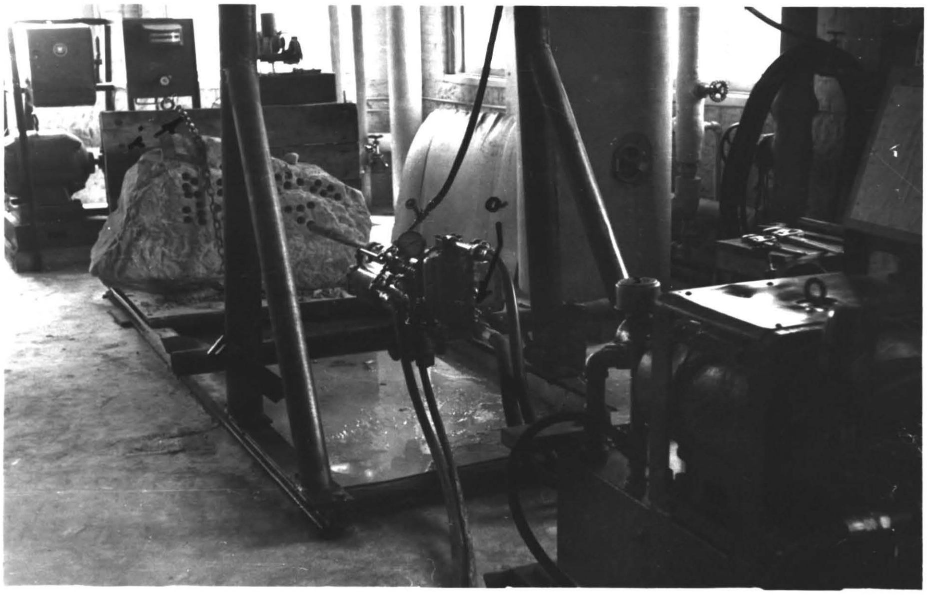

Figure 29. Rear view of complete drill setup.

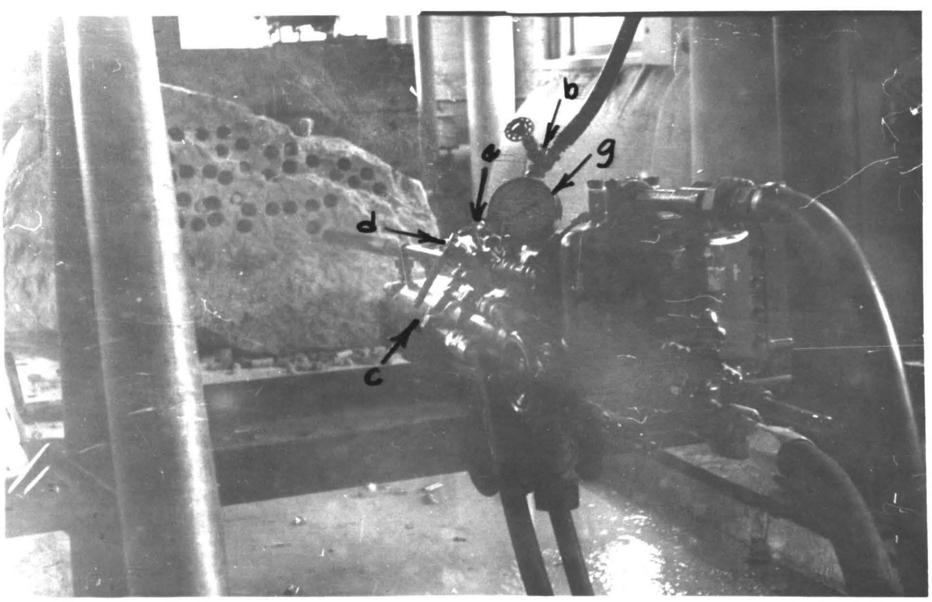


Figure 30. Rear view of drill showing drill rods and rock.

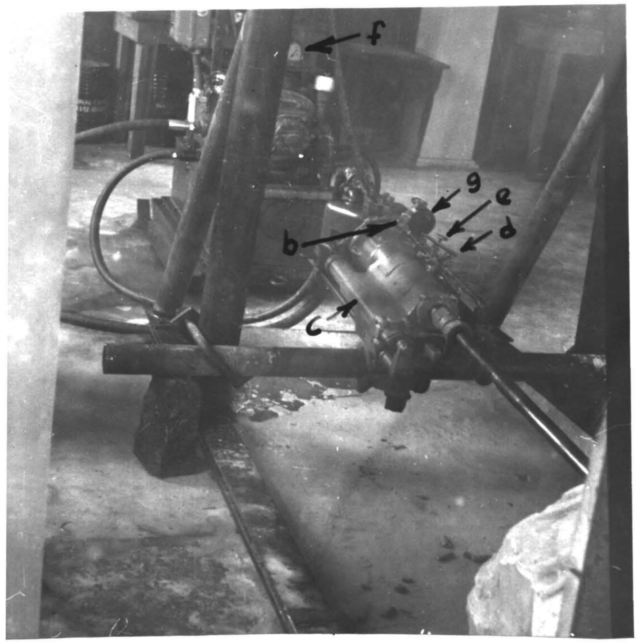


Figure 31. Front view of complete drill setup.

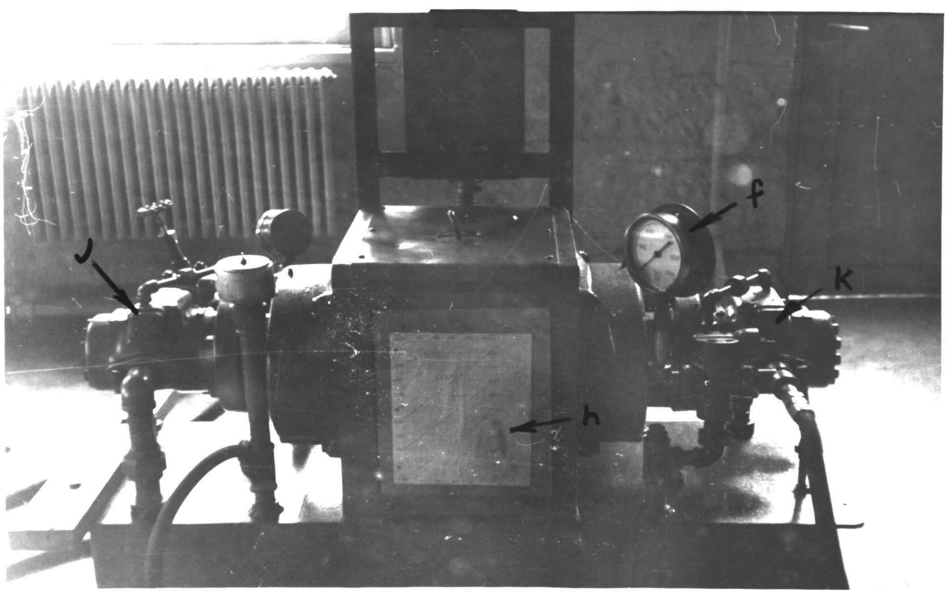


Figure 32. View of pumping unit.

Hydraulic Feed

The two hydraulic cylinders (c) give a stroke or feed of 20 inches. The total working area of the cylinders is 8 inches at the front or forward-feed end, whereas it is 8.9 inches at the back or rear-feed end. By turning the handle of the four-way valve (d) 45° to the left or 45° to the right of the center closed position, the oil circuit is changed to provide either a forward or backward movement of the drill. The rate of forward feed is controlled by the feed control valve (e). This valve allows the operator to change the pressure on the rear-feed end, thus controlling the forward-feed and force on the bit. The forward-feed pressure is recorded on the gauge (f) near the feed pump, while the rear-feed pressure is recorded on the gauge (g) on the drill. Thus, it is relatively simple to obtain the force on the bit by the formula:

(8 X forward pressure) - (8.9 X back pressure) = force on the bit. The author constructed the graph (h) which was placed near the drill for rapid computation of the force on the bit or, as it may be termed, the bit pressure.

Drill Base

With the aid of the Mining Department staff, the author constructed the base for the Rotobore Drill. The base consists of 11 feet, 60 lb. iron rails to which are welded and bolted four inch pipe for the vertical columns and three inch pipe for the braces. A three inch horizontal pipe is clamped to the four inch pipes by U-bolts. These U-bolts allow for easy vertical movement of the drill. Three foot pieces of the same rail are welded in a vertical position at the other end of the base rail. Triangular pieces of ½ inch iron are welded on as braces. Two inch by six inch timbers are bolted to the short pieces of rails.

The rock rests against the timbers and is supported by 3/8 inch sheet iron on four inch channel irons which rest on the long base rails. The rock is made fast by a chain and binder (i) similar to the type used on logging trucks.

When all of the bolts, binders, and timbers were fastened, the setup was very rigid and exhibited little vibration.

Tachometer

A stroboscope-tachometer (Strotac) was used to determine the rotational speeds. A white line was painted on the chuck and rods. When the line on the chuck was appearing the same number of times per minute as the light on the Strotac was flashing on and off, the revolutions per minute of the drill were the same as the revolutions per minute indicated on the Strotac.

# CONDITIONS OF THE TESTS

The primary objective of the research was to conduct the bit tests under controlled conditions and, if possible, under constant conditions. This meant that all of the drilling factors would be held constant and rate of advance would be recorded when this condition was attained. Throughout all the tests, the factors were controlled and in nearly all cases, the conditions were held constant for the length of time indicated on the data sheets (Appendix B).

## Method of Running a Test

The procedure used for testing the bits was as follows: (1) The hole to be drilled was collared with the starter bit (Figure 34) in order to prevent damage to the test bits. (2) The starter bit was replaced by the bit to be tested; the rotational speeds and bit pressures to be used were chosen. (3) Both the tachometer and the oil pumps were activated and water circulation was begun. (4) The drill was started at approximately the desired speed and the bit pressure was applied. (5) When the bit pressure and speed became constant at the selected point, a chalk mark was made on the drill base rods and the time was established. The drill was operated from the desired length of time, or until operating conditions were altered by some external factor. Cuttings were collected for screening at a later date. (6) At the end of the drill run, the time was recorded again and another chalk mark was made on the base rods. The machine was stopped and the amount of advance was measured and recorded along with the time, water flow, water pressure, bit force and rotational speeds. (7) The bit was examined to determine if it were damaged during the test.

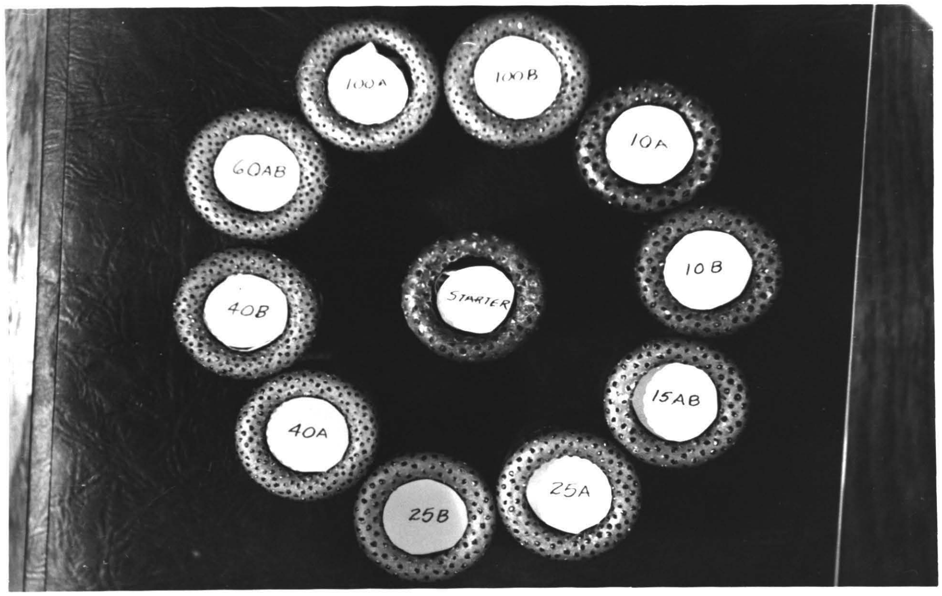


Figure 33. Composite picture of bits.

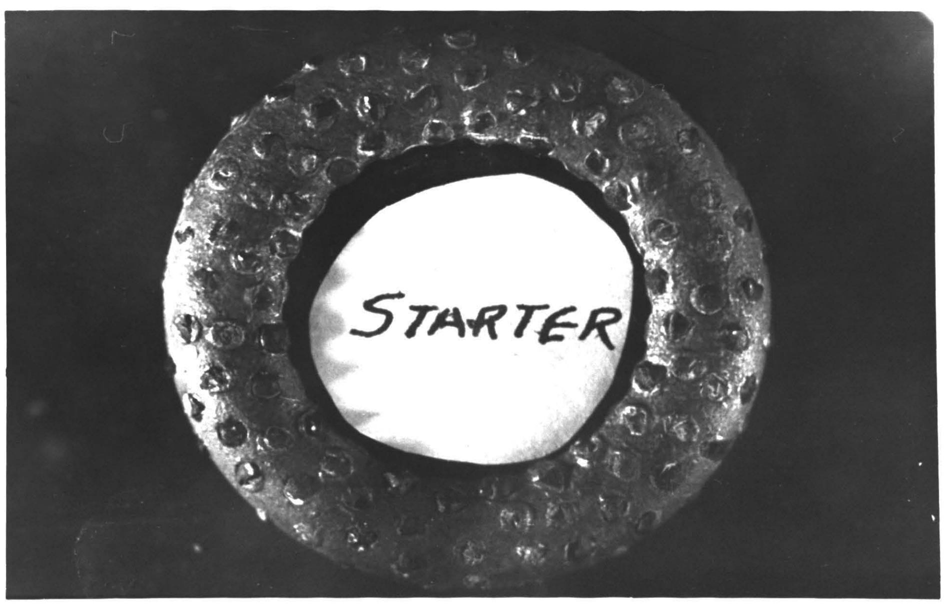


Figure 34. Starter bit used to collar holes.

Some of the elements responsible for departure from the established operating rotational speeds, bit pressures, water pressure and water flow, were: the presence of pyrite or quartz particles, the occurrence of a soft spot in the rock, the mudding or sludging up of the bit, poor circulation of the water, or the binding of the rods. When any of these factors appeared, it was necessary to halt the test.

The wear on the diamonds exerted by these tests is negligible. As previously mentioned, the bits were examined after each test and very little wear was noticed.

After completion of all the tests, the damage to the bits was found to be:

10 a --- 4 diamonds chipped.
10 b --- 3 chipped, 4 slightly chipped.
15 ab--- 2 slightly chipped
25 a --- 3 slightly chipped
25 b --- 2 slightly chipped
40 a --- 6 slightly chipped
40 b --- 5 slightly chipped
60 ab--- 3 slightly chipped
100 a --- 2 slightly chipped, 1 missing
100 b --- 2 chipped

The very slight damage to the bits would have no measurable effect on the rate of advance of the diamond bit. This would be further borne out by the fact that a diamond bit may be used to drill over 200 feet in rock similar to the one tested, whereas, not more than five feet were drilled with any bit. In reality, the bits were merely "Broken in".

The condition of the bits before and after the tests may be seen in Figures 9 through 28.

## RESULTS OF THE TESTS

The results are tabulated in Appendix B, Tables 4 through 13; they are shown graphically in Figures 35 through 45.

Inconsistencies in the tests and results prevent the drawing of smooth curves through all points. When working with rock, one sometimes notices that the results may be affected by differences in rock characteristics. An example of this effect occurs when the rate of advance is decreased by the presence of quartz or pyrite. Sometimes the diminution is so small that it will not be noticed and still, it will affect the average rate of advance. In contrast, the presence of a soft or shaly seam would produce an increase in the average rate of advance. Whenever a noticeable increase or decrease was detected, the test was halted or disregarded.

Even though a few inconsistencies penetrated the results, they were not allowed to change the natural form of the curves. In the author's opinion, this justifies the ignoring of the more erratic points without affecting the reliability of the curves.

A study of all the points showed thatfor each bit two to three results were too far removed from the general pattern to be called reliable. Accordingly, 70-80% of the findings were correct.

The curves were drawn, not to pass through every point, but rather to show the true performance of the bit under the prevailing test conditions.

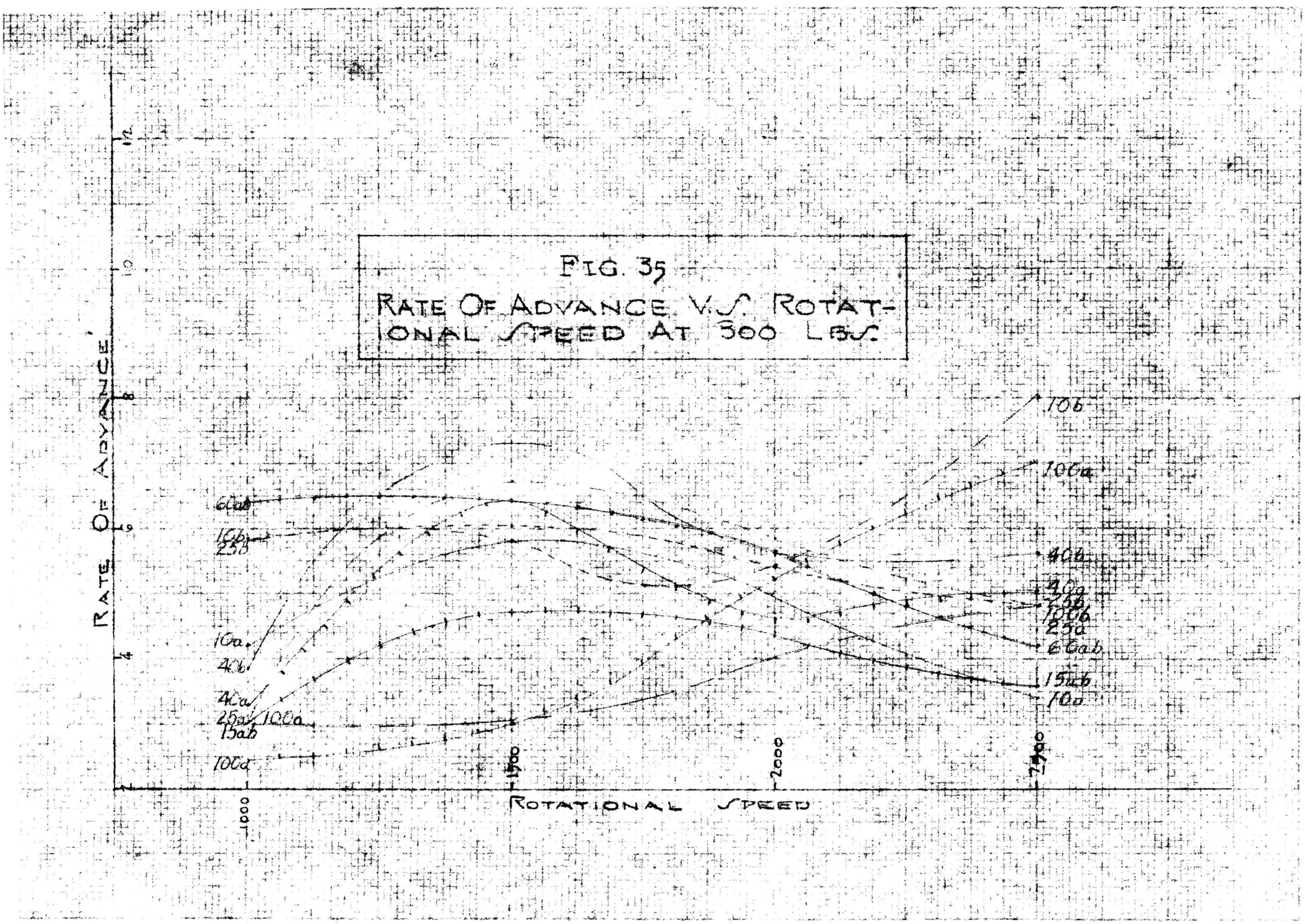
FIG. 35
RATE OF ADVANCE V.S. ROTATIONAL SPEED AT 300 LBS.
RATE OF ADVANCE
ROTATIONAL SPEED
1000
1500
2000
2500
10b
100a
40b
40a
25b
100b
25a
60ab
15ab
10a
60ab
10b
25b
10a
40b
40a
25a
100a
15ab
100a

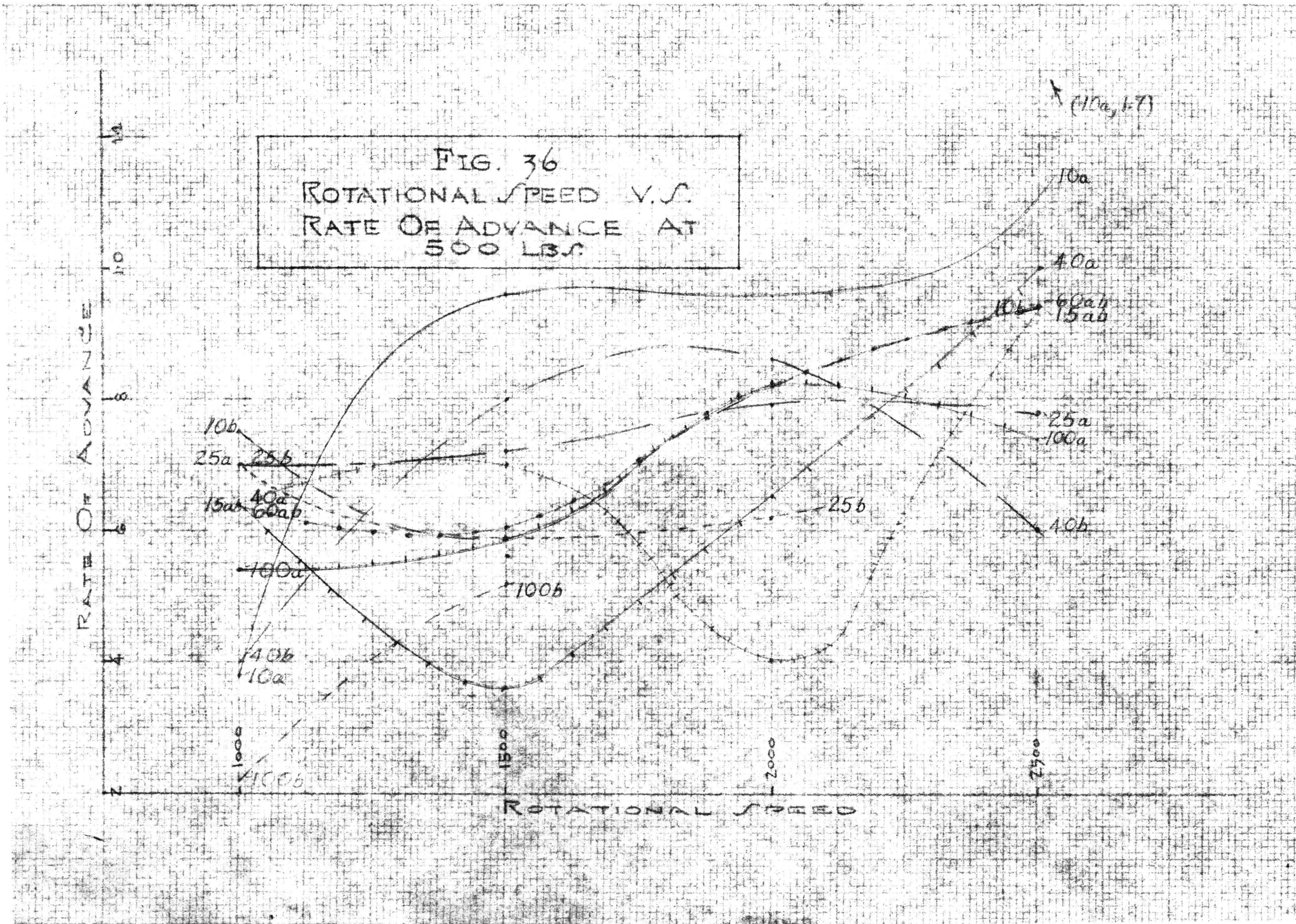
FIG. 36
ROTATIONAL SPEED V.S.
RATE OF ADVANCE AT
500 LBS.
RATE OF ADVANCE
ROTATIONAL SPEED
1000
1500
2000
2500
(10a, 1.7)
10a
40a
60ab
15ab
10b
25a
100a
40b
25b
100b
15ab

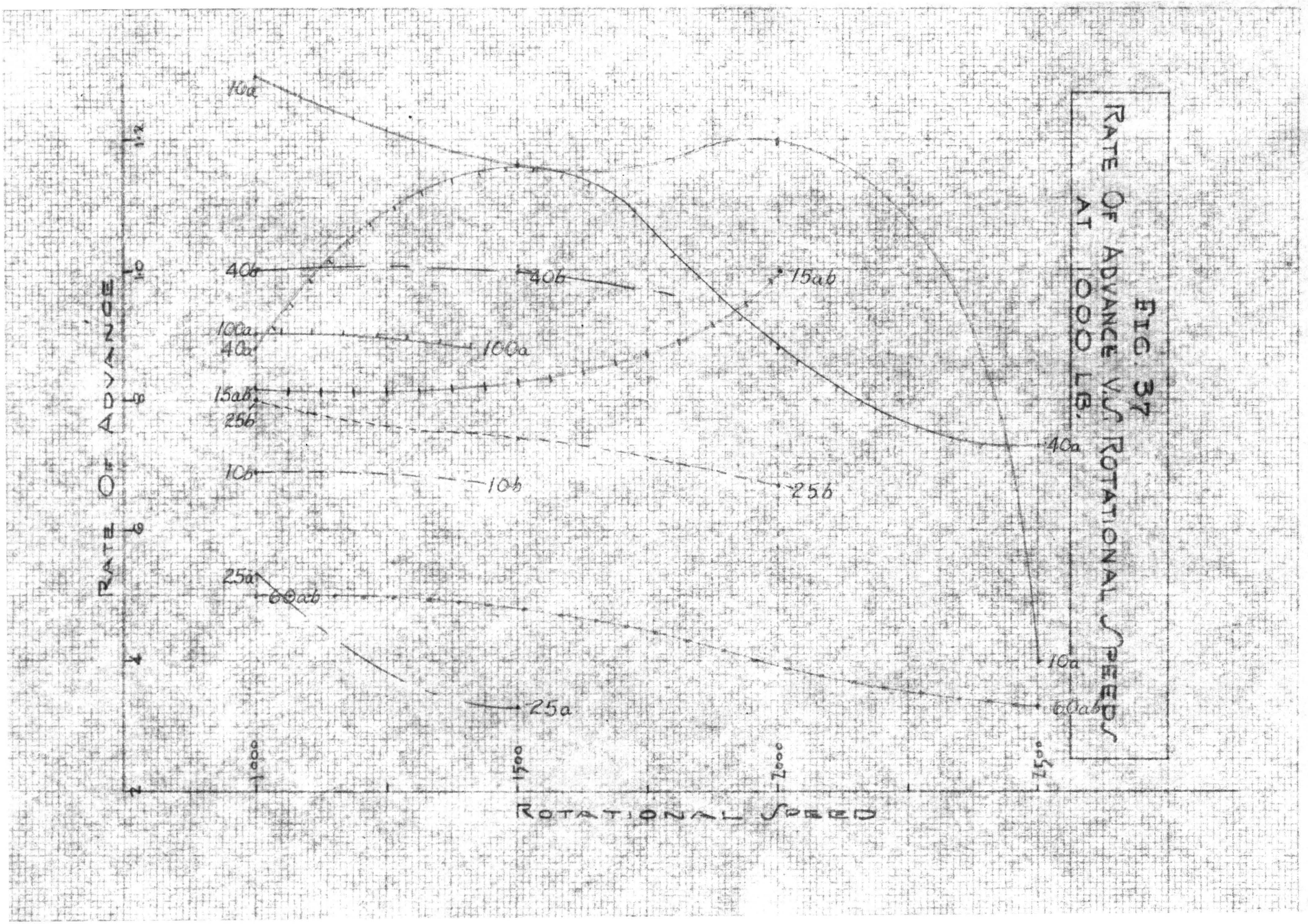


FIG. 37
RATE OF ADVANCE V.S. ROTATIONAL SPEEDS
AT 1000 LB.

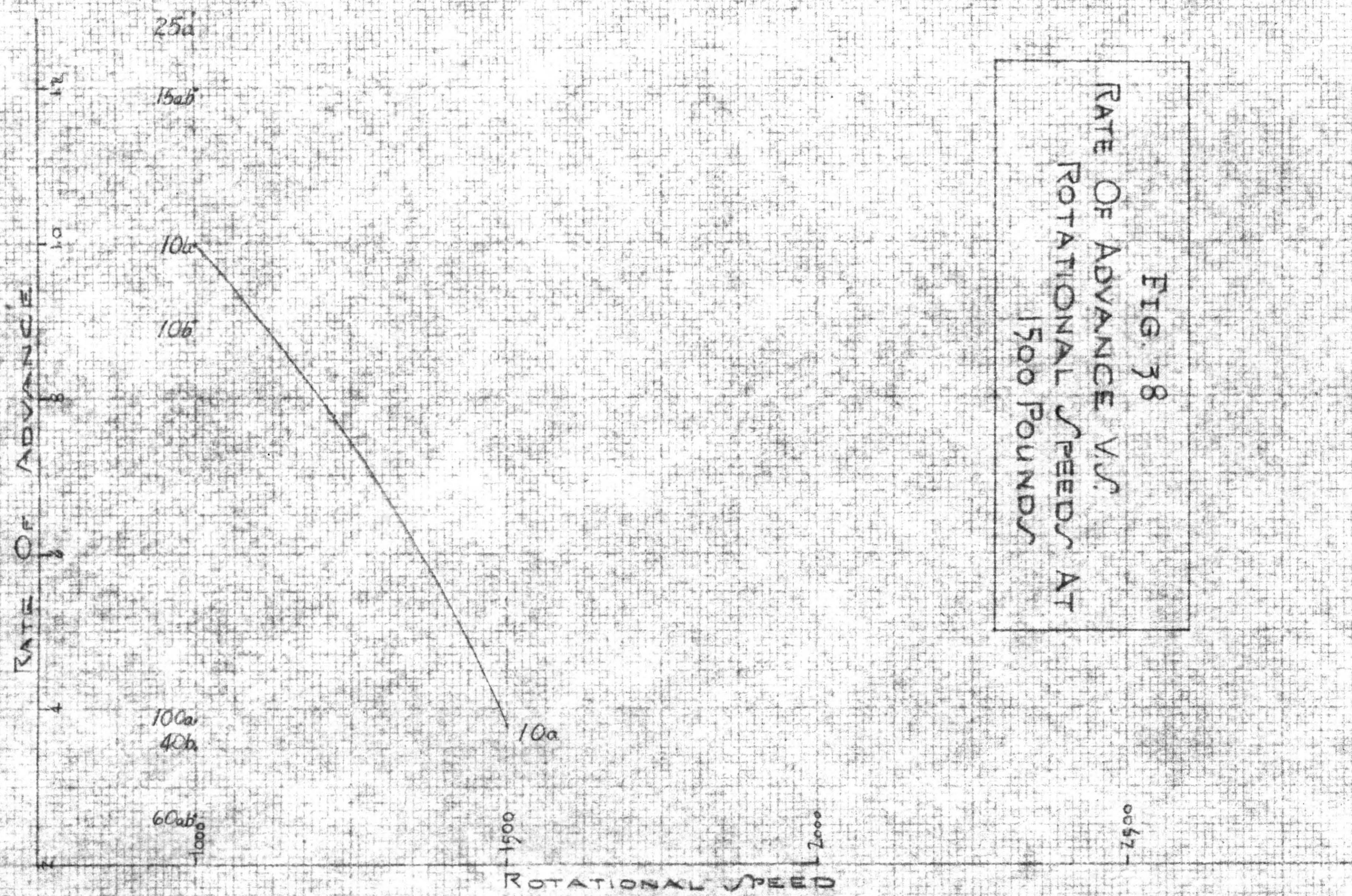


FIG. 38
RATE OF ADVANCE V.S. ROTATIONAL SPEEDS AT 1500 POUNDS

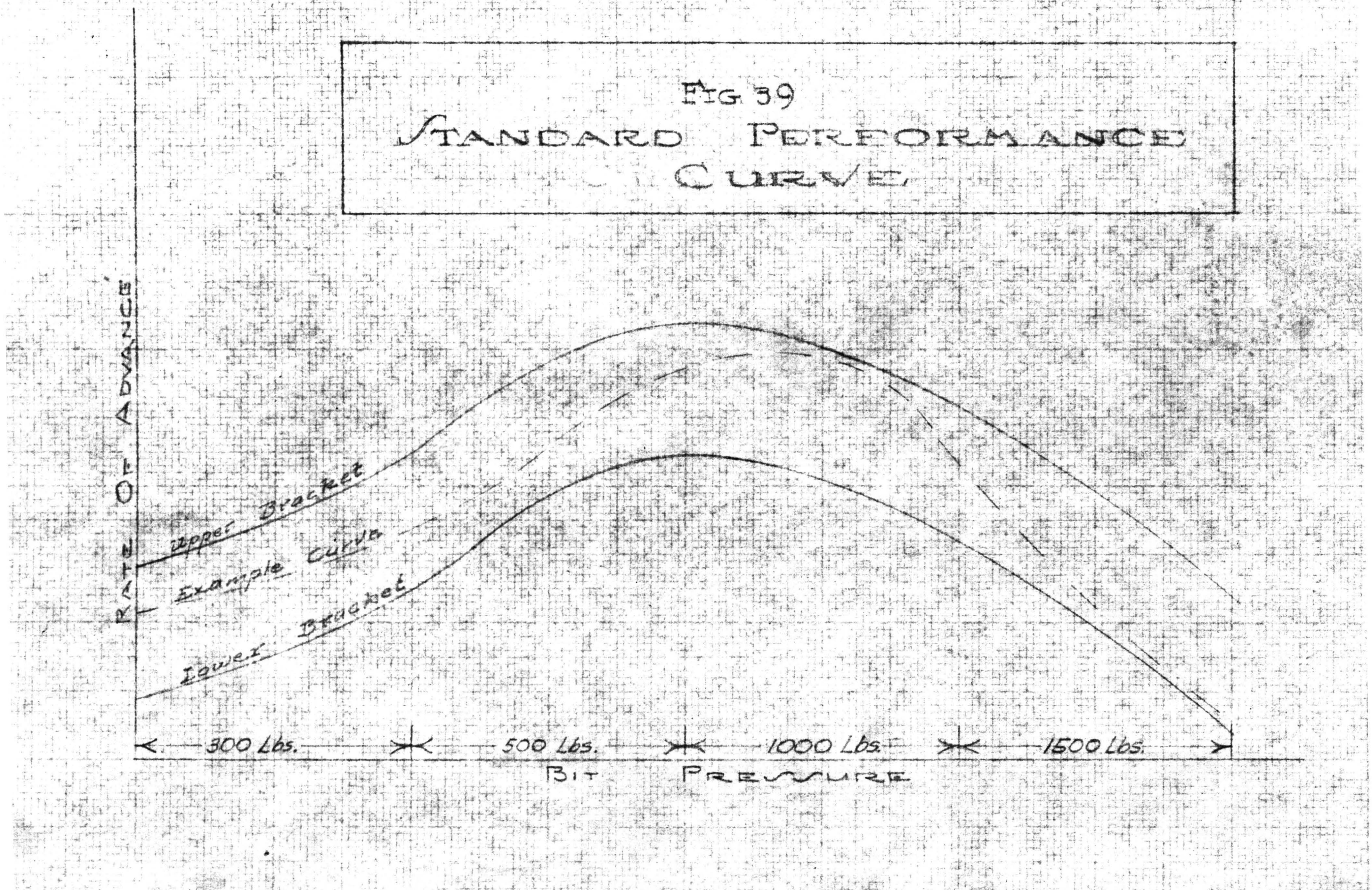

FIG 39
STANDARD PERFORMANCE CURVE
RATE OF ADVANCE
Upper Bracket
Example Curve
Lower Bracket
300 Lbs.
500 Lbs.
1000 Lbs.
1500 Lbs.
BIT PRESSURE

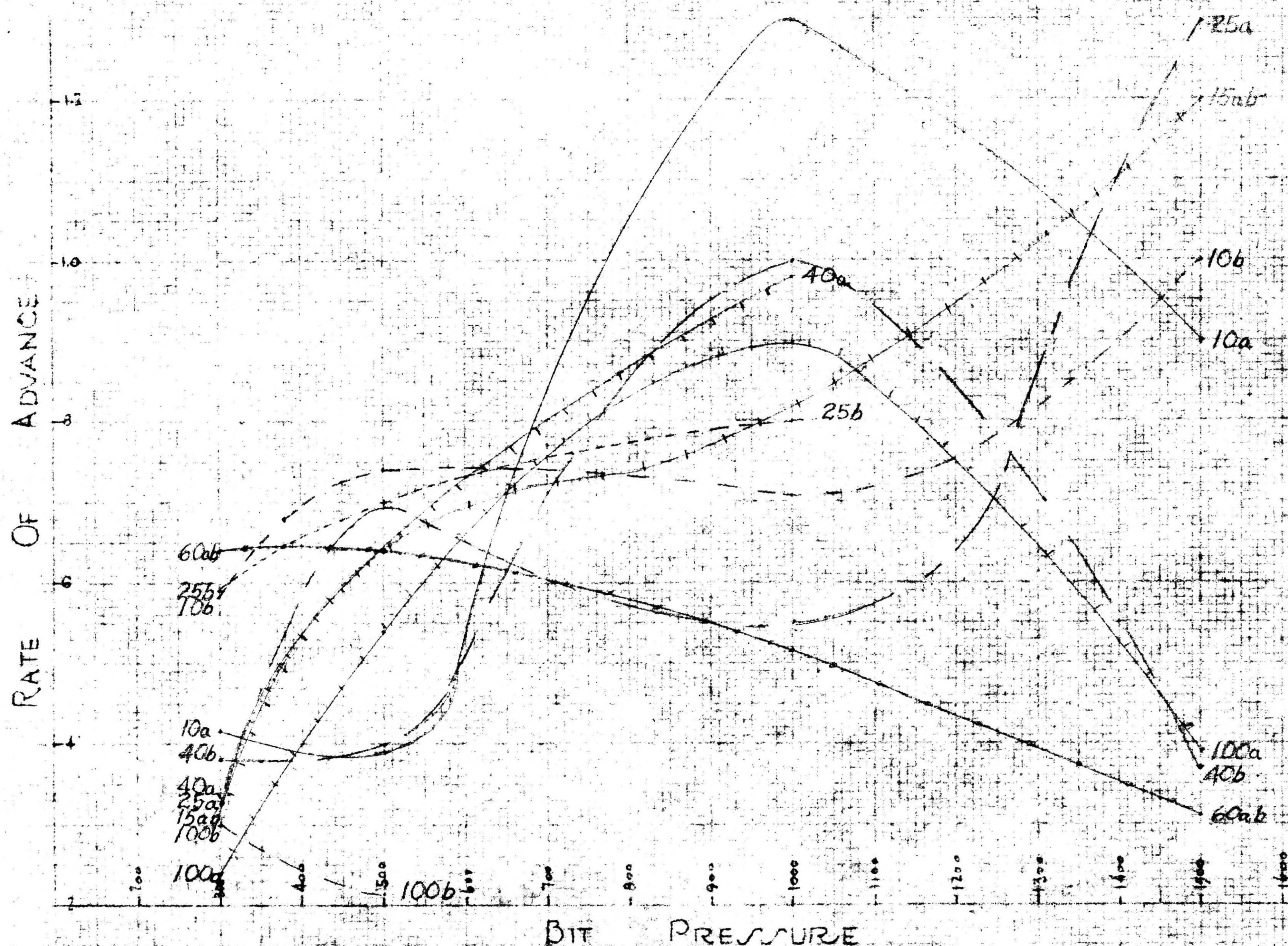


FIG 40
RATE OF ADVANCE V.S. BIT PRESSURE AT 1000 RPM

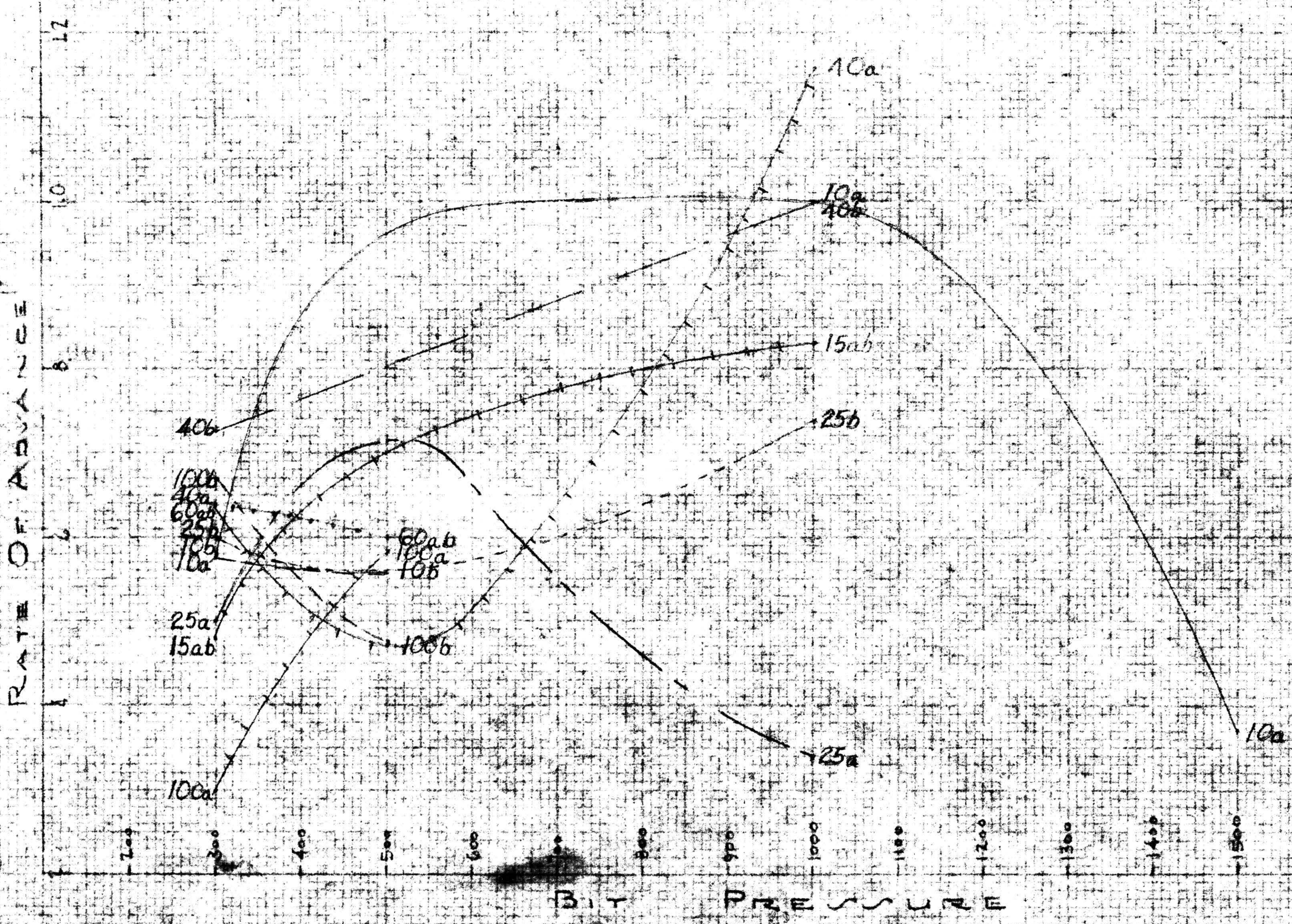


FIG. 41
RATE OF ADVANCE VS BIT PRESSURE AT 1500 RPM

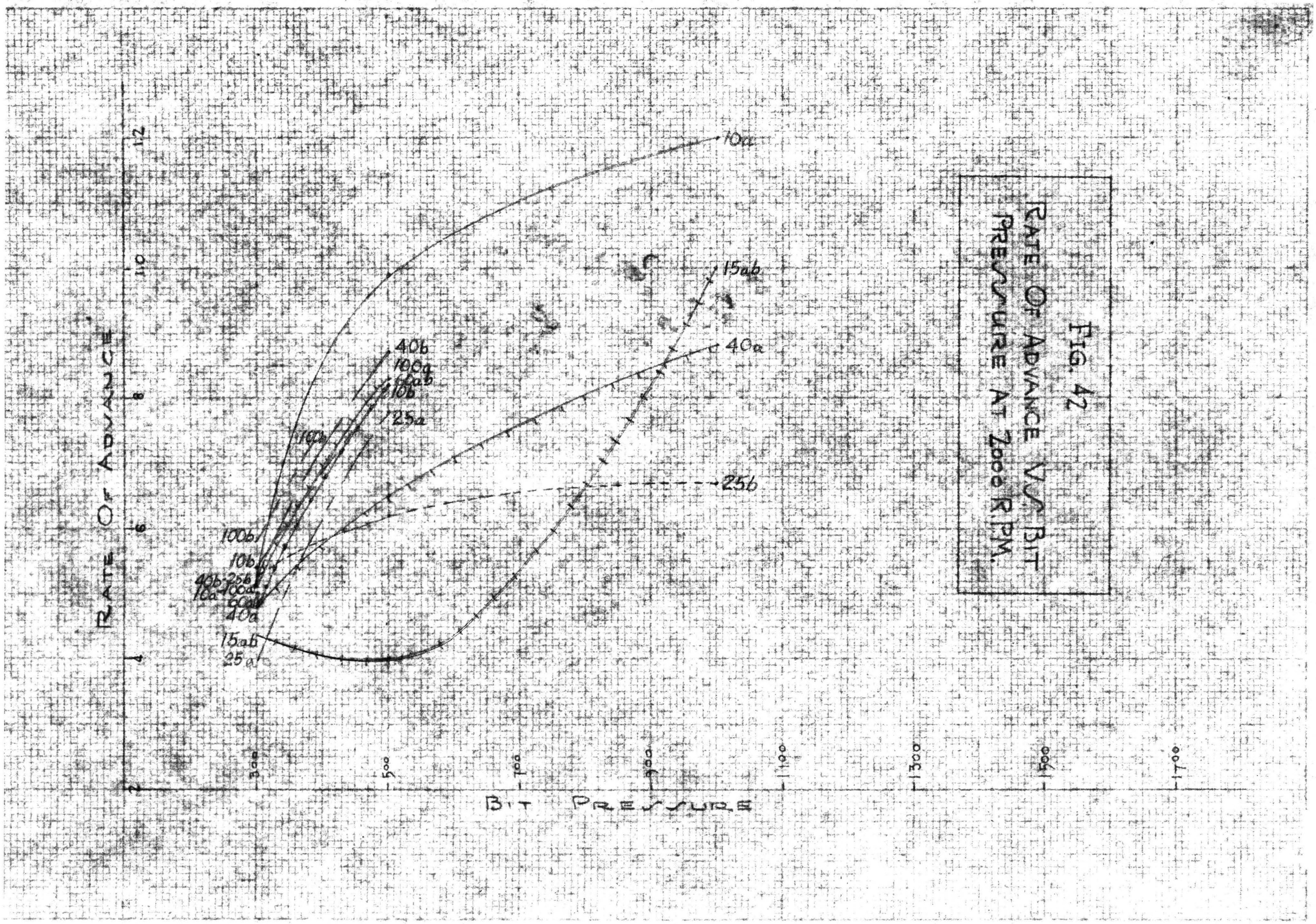


FIG. 42
RATE OF ADVANCE VS BIT
PRESSURE AT 2000 R.P.M.

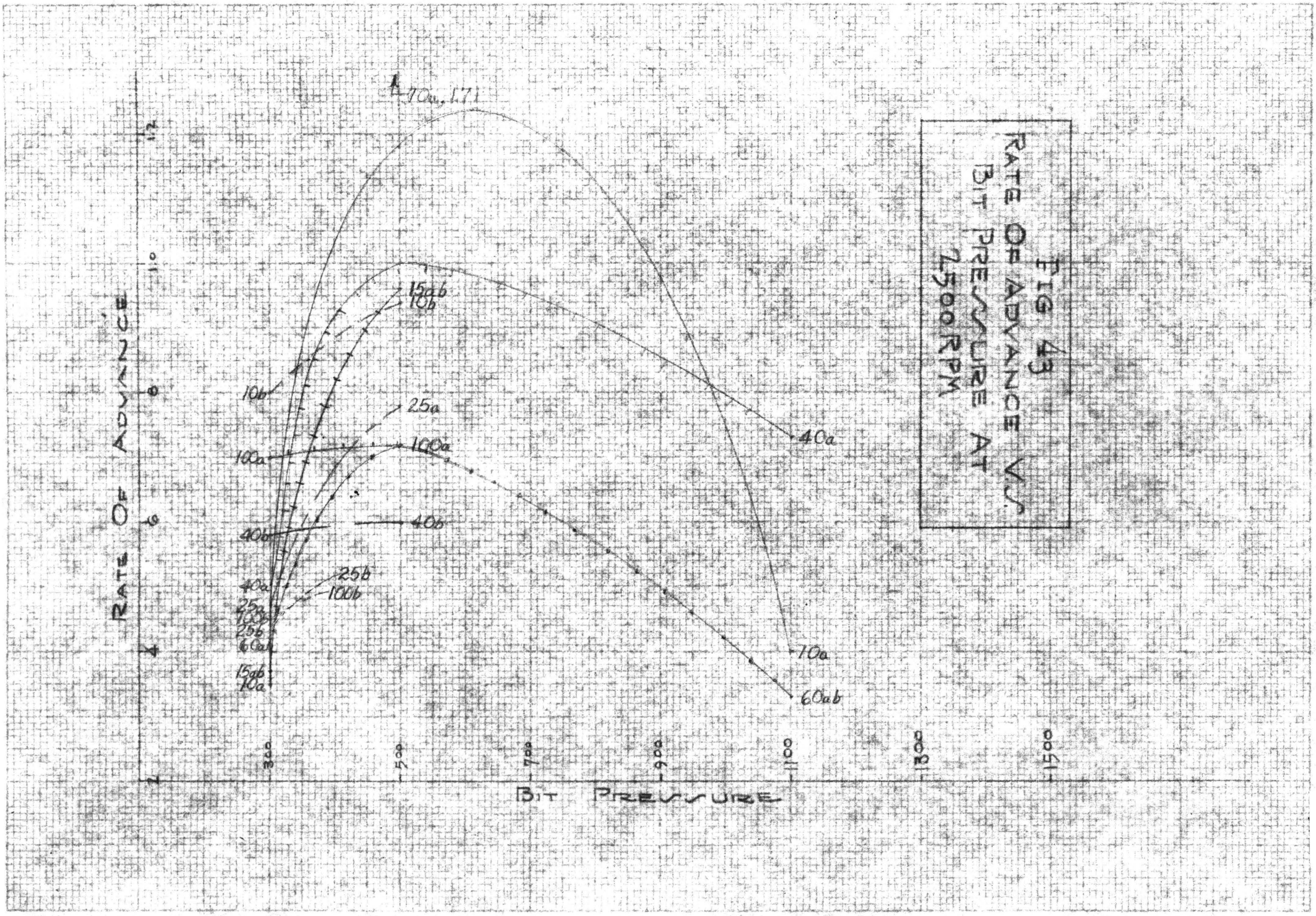
FIG 43
RATE OF ADVANCE VS
BIT PRESSURE AT
2,500 RPM
RATE OF ADVANCE
BIT PRESSURE
70a, 171
15ab
10b
10b
25a
100a
100a
40a
40b
40b
25b
100b
40a
25a
100b
25b
60ab
15ab
10a
70a
60ab
1.2
1.0
.8
.6
.4
.2
300
500
700
900
1100
1300
1500

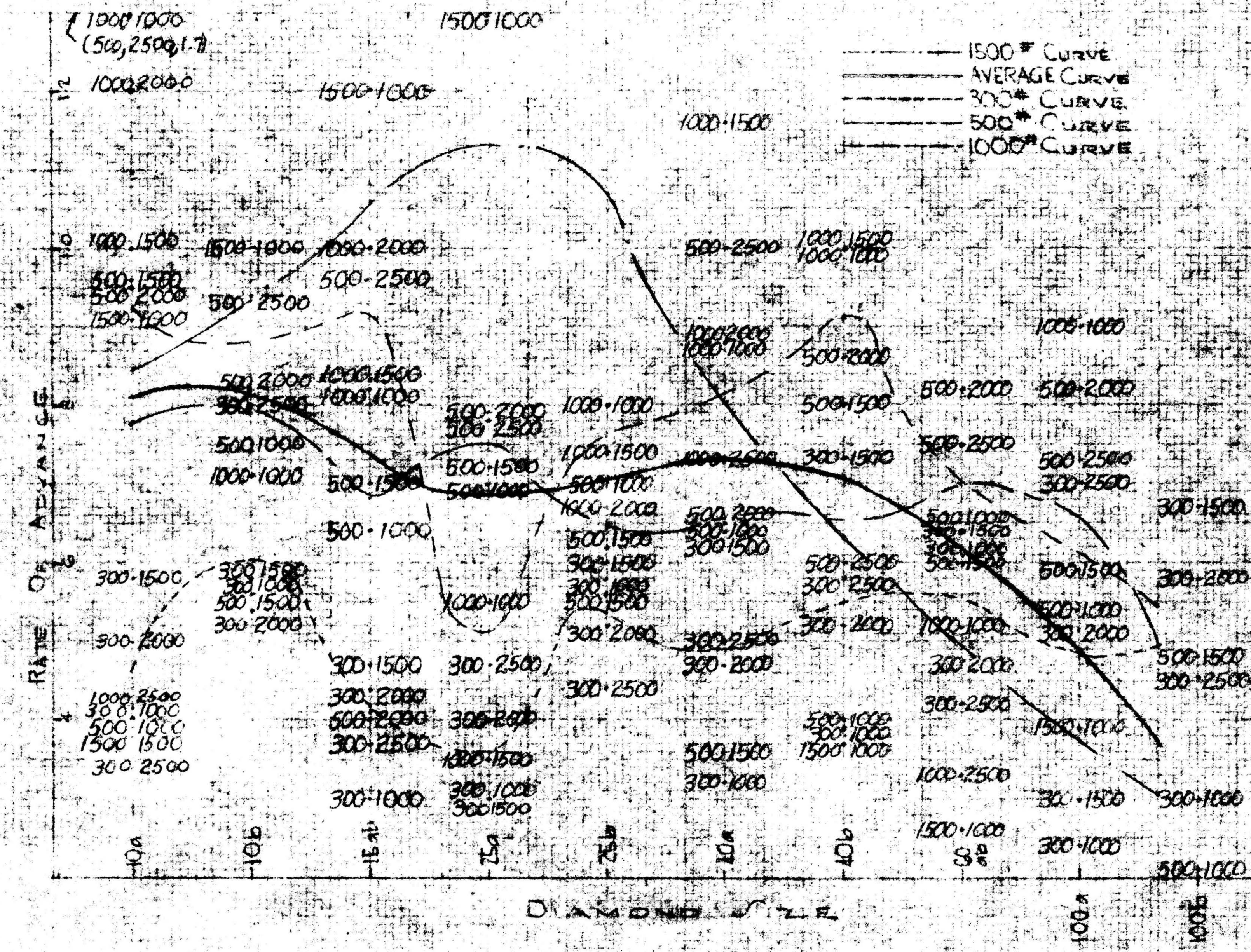


FIG. 44
RATE OF ADVANCE VS SIZE OF THE DIAMOND

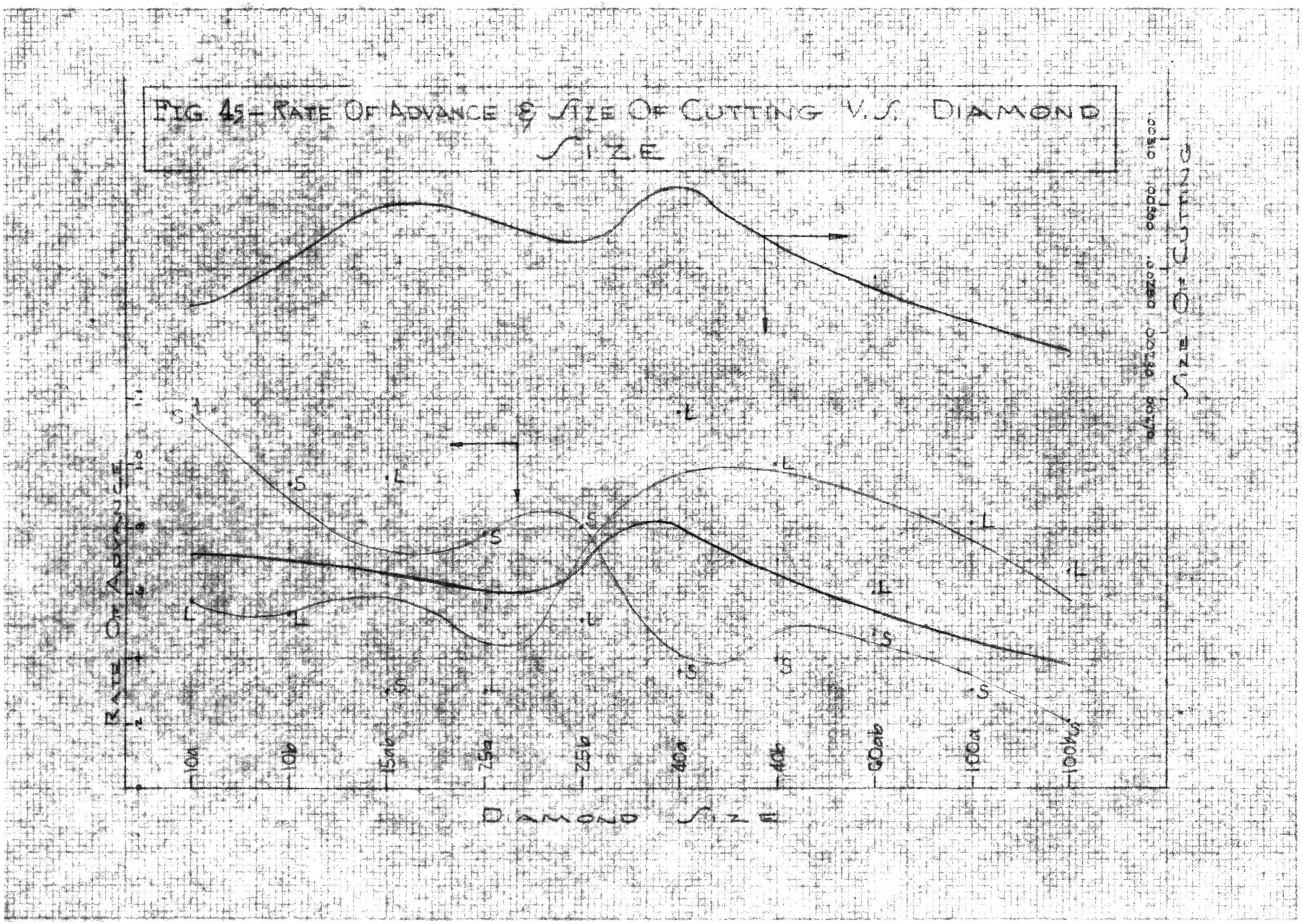


FIG. 45 - RATE OF ADVANCE & SIZE OF CUTTING V.S. DIAMOND SIZE

## INTERPRETATION OF RESULTS

One question which confronted the author was, "Which factors affecting the results are the most influential?". The variable which affected the results most, other than the size of diamonds, was the force on the bit. The rotational speeds seemed to be of lesser importance. The efficiency of the water circulation also influenced the results.

Figures 35 through 38 show for each bit the rate of advance versus rotational speeds at each of the four bit pressures. A composite of these graphs would resemble closely the standard performance curve in Figure 39. The slopes of the curves may vary at adjacent points as indicated by the example curve, but all of the curves would occur probably between the upper and lower brackets.

Figure 35 shows that 300 pounds bit pressure is not sufficient to give the bits a good test. Figure 38 indicates that for most of the bits, 1,500 pounds bit pressure is too high for drilling in dolomite.

Graphs 40 through 43 are the diagrams for each bit showing the rate of advance versus the bit pressures at each of the four rotational speeds. Each of the graphs seems to be a performance curve in itself.

Figures 35 through 43 will be interpreted according to bit relationships. The series were picked by comparing each bit with any other that had anything in common with it, i.e., exposures, number of diamonds, pattern, or size of diamond.

<u>Comparison of Bits 10a and 10b</u>

| | | |
|---|---|---|
| 10a | 96 stones | 13.14 carats |
| 10b | 120 stones | 16.55 carats |

The natural assumption would be that the 10b bit would cut better than 10a, as it had more cutting edges of the same size. This appeared to be true at the lower pressures, but as the pressures increased the 10b apparently cut or crushed more rock than could be carried away by the water. This caused the rate of advance to decrease. Although the exposures theoretically were the same for both of the bits, it seemed that the diamonds in the 10b bit protruded less than those in the 10a bit. This fact would help account for the decrease of rate of advance at higher pressures, as there would be less room for the cuttings to escape.

Comparison of Bits 10a, 15ab, and 25a

| | | |
|---|---|---|
| 10a | 96 stones | 13.14 carats |
| 15ab | 120 stones | 10.01 carats |
| 25a | 144 stones | 8.19 carats |

The 10a bit had fewer stones than the 15ab, which, in turn, had fewer stones than the 25a. A study of Figures 35 through 43 shows that almost without exception the 10a bit drilled the fastest followed by the 15ab and 25a bits. This shows conclusively that for these three bits the size of diamond was a definite factor. Even though the 25a bit had about 50% more stones than the 10a bit, the 10a cut up to three times as fast. This would indicate that there might possibly have been a difference in the cutting action, as discussed in the conclusion.

Comparison of Bits 10b, 15ab, and 25b

| | | |
|---|---|---|
| 10b | 120 stones | 16.55 carats |
| 15ab | 120 stones | 10.01 carats |
| 25b | 120 stones | 6.96 carats |

The drilling efficiency of the bits seemed to be in the descending order: 10b, 15ab, and 25b. An exception to this general statement occurred at the higher bit pressures (1500#) when the 15ab and 25a drilled better than the 10b. This may be explained again by the fact that the 10b simply cut more rock than could be carried away by the sludge removal medium. The author noticed that the water coming out of the hole seemed to be muddy, a sort of slurry, and much more viscous than if good water circulation and sludge removal had been taking place.

The 25b bit probably drilled slower than the 15ab because the smaller 25 p.c. stones did not give the complete coverage obtained with the larger 15 p.c. stones.

Comparison of Bits 25a and 25b

| | | |
|---|---|---|
| 25a | 144 stones | 8.19 carats |
| 25b | 120 stones | 6.96 carats |

At the lower bit pressures (300#) the 25b bit drilled better than the 25a, for although there was not enough pressure for either to drill very well, the 25b had more pressure per diamond than the 25a. As the bit pressures went up to (500#) the 25a, with more stones, got a larger amount of pressure per stone and drilled better. The 25b bit also drilled better, but with fewer stones did not cut as much material per unit of time. The 25a bit at 1,000 pounds bit pressure cut more material than could be carried away effectively. The 25a bit drilled rapidly at 1,500 pounds, but only for a short time. After the test was completed, the bit appeared to be clogged with mud.

Comparison of Bits 40a and 40b

| | | |
|---|---|---|
| 40a | 196 stones | 6.03 carats |
| 40b | 224 stones | 6.90 carats |

The 40a bit should not have drilled as well as the 40b bit, as the latter had more diamonds. The 40b bit drilled slightly better than the

40a bit at lower bit pressures. However, the 40b bit cut more material at 1,500 pounds than could be carried away. This made some regrinding necessary.

The diamonds in the 40a bit, having a thinner plot, are farther apart than in the 40b bit. Therefore, the distance between ridges and groves in the rock will be greater. This fact caused the 40a bit to produce larger cuttings. These larger cuttings seemed to be the optimum size which the water could carry away.

Comparison of Bits 40a, 60ab, and 100a

| | | |
|---|---|---|
| 40a | 196 stones | 6.03 carats |
| 60ab | 224 stones | 5.33 carats |
| 100a | 252 stones | 4.33 carats |

The 60ab bit, because of additional diamonds, drilled slightly better at 300 pounds bit pressure than the 40a. Neither bit was drilling up to its capacity.

The additional diamonds in the 60ab bit were compensated for by the larger diamond in the 40a bit at 500 pounds bit pressure. The 100a bit exhibited slightly less efficiency than did the 40a and 60ab bits.

The 40a bit drilled faster at 1,000 pounds bit pressure than either of the other two. The 60ab bit passed its peak performance and its efficiency was declining. The 100a bit did not drill more than a few inches without clogging.

At 1,500 pounds bit pressure all of these bits passed their peak performances. None of these bits should have been operated at this high pressure in dolomite.

Comparison of Bits 40b, 60ab, and 100b

| | | |
|---|---|---|
| 40b | 224 stones | 6.90 carats |
| 60ab | 224 stones | 5.33 carats |
| 100b | 224 stones | 3.82 carats |

The 40b bit drilled faster than either the 60ab or 100b bits because of the larger diamonds in the bit.

The 60ab bit drilled faster than the 100b at 500 pounds as the 100b plot was definitely too loose for the dolomite.

At 1,000 pounds bit pressure the 40b bit was by far the best of the three. The 100b bit would not even drill.

It is the author's opinion that the rock was soft enough to let the 100 p.c. diamonds penetrate it. This allowed the metal part of the bit face to rub against the rock causing the bit to stop rotating as little water could circulate.

None of the bits drilled efficiently at 1,500 pounds bit pressure.

Comparison of Bits 100a and 100b

| | | |
|---|---|---|
| 100a | 252 stones | 4.33 carats |
| 100b | 224 stones | 3.82 carats |

The 100a bit drilled much better than the 100b except at the lowest bit pressures (300#) when the force per stone was too low for the 100a bit. Any pressure over 300 pounds was too great for the 100b bit, and it then would not drill. As previously mentioned, the author visualizes a complete penetration of the small 100 p.c. stones under the high pressures. The plot for the 100b was definitely too loose.

Analysis of Size of Cuttings Versus Rate of Advance

The author selected cuttings from certain tests which he considered reliable. These tests gave the highest and lowest rates of advance for each bit.

The cuttings were taken from the water coming out of the drillhole when the drill was advancing at a uniform rate under constant conditions. The cuttings were screened and analyzed to determine the average size. These sizes were plotted against diamond size as was rate of advance for the specific tests. These results appear in Figure 45.

The tests seem to be reliable when one compares the average rate of advance curve in Figure 45 to the average rate of advance curve in Figure 44. One can see that they are almost identical.

A comparison of the average rate of advance curve and the average size of cuttings curve in Figure 45 shows that there is a definite relationship between the curves. One might surmise that the same factors produced these curves.

A more intensive study gave the author the idea that there was a difference in cutting action as the bits were gradually changed from the 10a bit through to the 100b bit.

On the 10a side of the curve, the rate of advance is high, but the cuttings are small. This indicated to the author that either the large pieces were being torn out by the 10a diamonds and broken up or the large diamonds were drilling with a crushing action. If this crushing action were taking place, there would not be full penetration of the diamonds.

The cuttings from the 10b bit were slightly larger than those from the 10a bit. This might be explained by the fact that the diamonds initially were cutting particles which were smaller than the 10a particles, as the diamonds were closer together in the 10b bit. However, the smaller 10b particles were of a size that could be carried out better in the sludge removal medium. Therefore, there was more regrinding with the 10a than with the 10b bit. At the start the 10a cuttings were larger than the 10b cuttings. Regrinding of the 10a cuttings produced many small particles and ultimately brought the average size of cuttings from the 10a bit below that of the 10b bit. There apparently was some regrinding of particles with the 10b bit and in all the sizes up to the 40a bit cuttings.

The proof that regrinding is impractical is derived from Rittenger's Law which states, "Work done (or energy used) in crushing is proportional to the area of new surface created." Astronomical figures for area of new surface created are obtained when even a cubic centimeter of rock is pulverized. Therefore, much more surface is created and more energy lost in this case in which much more rock is broken out and reground.

The particles derived from the 15ab and 25a bits were probably even closer than the 10a and 10b to the optimum size for efficient drilling. The 25b bit initially gave cuttings larger than the optimum size. These cuttings had to be reground in order to be removed. In the beginning the 25b cuttings were larger than the 25a cuttings because the plot was more open than the 25a plot. The 25b bit was made in the same mold as the 15ab bit. This setting of smaller diamonds in the same mold had the effect of loosening the plot, putting the diamonds farther apart, and producing larger cuttings. Regrinding, as related before, reduced the cuttings to the smaller sizes.

The 40a bit apparently penetrated the rock the right amount and broke out the optimum size cutting which could be carried away efficiently by the sludge removal medium. The largest sizes cuttings along with the fastest average rate of advance indicated to the author the most nearly perfect cutting action. Penetration into the rock, breaking out of the optimum size of the particles, and carrying away of these particles with a minimum of grinding would constitute this action.

The 40b bit, having a tighter plot than the 40a bit, cut out particles which were slightly too small. These particles were carried away with a minimum of regrinding, but too much energy was expended in the original breaking out of the smaller size cuttings. The same type of analysis would apply to the 60a, 100a, and 100b.

A diamond bit, when drilling rock, will leave ridges of rock between adjacent stones. The following stone to move along this ridge will break it out if the stone is large enough. Smaller stones do not shatter the ridge as effectively as do the larger stones. This analysis indicated the effects of the size of diamond on drilling efficiency.

## CONCLUSIONS

The author, as a result of the research he conducted, has come to some definite conclusions concerning the size of diamonds in diamond drilling. Even though the author's impressions were gained from tests in one rock type, they may be extrapolated to include others, especially other soft rocks.

Some of the salient points disclosed by the drilling were:

1. The size of stones in a diamond drill bit directly influences the drilling efficiency of the bit. Under identical conditions, a bit containing larger sized diamonds consistently drills twice as fast as one containing smaller stones. A bit containing relatively few large diamonds drills better under similar circumstances than a bit containing many more smaller stones. This indicates that although the number of stones or cutting points is important, the size of the stones is also significant. It was possible to determine the best size of diamond for drilling this rock. This ideal size may change to some extent as the diamond wears away.
2. The cutting action of a diamond bit in dolomite consists of breaking out of rock particles so that they may be washed away. If the particles are small, they will be carried away by the water with little regrinding. However, if the cuttings are large, it will be necessary to regrind them to a size which can be removed by the water. The fragments must be small enough to pass between the

bit and rock and also between the drill rods and the side of the hole.

A point was reached in this research where the largest size rock particle was broken out and carried away with a minimum of regrinding. The most efficient cutting action, a direct consequence of the size of diamonds, was constituted by this drilling practice.

All the tests were run with relatively new bits so it was impossible to tell how wearing of the stones would affect the cutting action and drilling efficiency.

3. The optimum operating conditions for any of the bits tested may be found by consulting the graphs and tables included in this paper. It is possible to determine from them the best rotational speeds, bit pressures, and size of diamond.

   The flow of water through the rods and past the bit was not varied. The author is confident that higher water pressures and quantities would have proved fruitful in increasing the drilling efficiency. This would have been especially true when using the bits containing larger stones. The water, circulating with a higher velocity, could have carried out the cuttings with less regrinding.

4. No bit designed for use in dolomite should contain stones smaller than 40 per carat. The 60 per carat and 100

per carat bits were too small to drill efficiently. The bits employed in drilling dolomite should have coverage because the rock is soft. If the bit is against the face, each diamond cuts a groove equal to the amount of diamond exposed. There is probably less side breakage in dolomite than in a harder rock like granite.

5. If the rate of advance is compared to the bit pressure, all bits tend to perform along the lines indicated in the standard performance curve, Figure 39.

6. The author considers it pertinent to make a few suggestions concerning bit design.

   a. A bit made with the same basic pattern as used in these tests, but with fewer repetitions of the pattern, might cut as well as or better than the present design. For example, the bit might still have a five stone face pattern but fewer governing kicker stones. The total number of stones, therefore, would be reduced.

   b. It might be feasible to test a series of rocks covering the main rock types. The manner of testing could be similar to the one used on these tests. If relationships could be drawn between size of diamond, rate of advance, and size of cuttings for a series of rocks, the optimum size of diamond could be chosen more easily.

   c. A bit made up of about one half 15 p.c. stones and the remainder 40 p.c. stones might drill well in dolomite. The larger stones could be placed to make the original grooves in the rock and the smaller ones to break out the remaining ridges. This method would provide complete face coverage.

d. A bit made with tungsten carbide or some other substance which has high shock and impact resistance might be designed to collar the holes.

## SUMMARY

A series of tests was conducted using bits for the purpose of evaluating the effect of the size of diamonds in diamond drilling. These tests were carried on in a fine-grained homogeneous dolomite of the Ordovician Jefferson City Formation.

Bits were designed using six different sizes of diamonds ranging from 10 per carat to 100 per carat. The bits were classified into two series, "A" and "B". The "A" series contained bits of two types, those with either a four or five stone face arrangement. There were three bits of each face arrangement type. The only differences among the three bits were in the number and size of stones. It may be said, generally, that as the diamond size decreased, the number of stones increased. The diamond exposures decreased as the size of stone decreased.

The "B" series was composed of two sets of two bits each. The purpose of this series was to test the effect of the size of diamonds. This was done by setting larger or smaller diamonds, as the case may be, in the same mold as another diamond bit had been set in. The result of this setting was two sets of three bits each having an equal number of stones in the same pattern. The exposure was the only variable changed. Photographs of the bits were taken before and after drilling.

With this set of 10 bits, it was possible to test the effect of size of diamonds in drilling the dolomite. The results may be extended to include other rocks of the same type.

The drilling was done with a Longyear Rotobore Diamond Drill. The drill was operated by an oil motor and hydraulic feed, each empowered

by an electrically driven oil pump.

The factors which affect the efficiency of diamond drilling are multitudinous in number. This makes it very difficult to evaluate data. The object of this research was to hold all of the drilling conditions constant except a few, i.e., size of diamond, rotational speeds, and bit pressures. These would be varied at will.

In a typical test the hole was collared with the special starter bit; the bit to be tested was put on and the drill was started at the predetermined rotational speed and bit pressure. When these factors and the rate of advance became constant, the drill was allowed to operate for a measured time. At the end of this period the drill was stopped, and the bit was examined for wear. The period of operation and amount of advance were recorded along with the other test conditions. Cuttings were collected and screened for size.

The recorded information was plotted on graphs to show the relationships between the different bits under varied conditions. These relationships were compared to the size of cuttings.

The cutting action and the data shown on the graphs were analyzed.

The author drew his conclusions from observations and data recorded on the graphs.

As a result of these tests it may be said that:

1. A direct relationship exists between the size of diamond and the drilling efficiency of a diamond bit. A similar relationship exists between the size of diamonds and the size of cuttings.

2. The best cutting action takes place when using a 40 p.c. bit. The action consists of breaking out particles of a

size which can be carried away by the water with a minimum of regrinding.

3. The best operating conditions in dolomite for any bit tested may be found in the included graphs.

From the information recorded, it was possible to speculate on the future design of diamond drill bits for drilling dolomite and other rocks.

## APPENDIX A

The stone drilled is these tests is a grey-blue dolomite. It is a fine-grained, dense rock taken from Bray's Quarry located about two miles south of Rolla, Missouri on U. S. Highway 63. The rock was obtained from the Ordovician Jefferson City formation about 55 feet above the upper surface of the well known Quarry Ledge. The rock is very homogeneous when compared to other available rocks , i.e., granite, limestone, or sandstone which might have been tested. There are, however, a few impurities, some of which are: layers; blebs, nodules and lenses of pyrite; occasional shaly layer; and fine, crystalline seams, blebs and rosettes of quartz.

The rock drilled contained, as far as could be determined, some pyrite and very little quartz. It could be said that the rock was very nearly of uniform composition and it suited the requirements of homogeneity as well as any which could be obtained.

Analyses of the rock conducted for the author by the Missouri Geological Survey and Water Resources gave the following results for three samples:

| Sample | Ca, $Mg(CO_3)_2$ | $FeS_2$ | $SiO_2$ |
|---|---|---|---|
| 1 | 99.8% | .1% | .1% |
| 2 | 99.7% | .1% | .2% |
| 3 | 99% | .1% | |

These figures will attest to the homogeneity of the rock used.

# A P P E N D I X B

TABLE 4

Bit Number 2987 Z 544 Stone Size 10 p. c. Total Carats 13.14
Type 10 a No. Stones in Bit 96 Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water gpm | Water psi | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | .31 | 300 | 1000 | 4 | 40 | .75 | .31 | .414 | good | | |
| 2. | .60 | 300 | 1500 | 4 | 40 | .5 | .29 | .58 | good | .00285 | |
| 3. | .85 | 300 | 2000 | 4 | 40 | .5 | .25 | .5 | good | | |
| 4. | .94 | 300 | 2500 | 4 | 40 | .25 | .085 | .34 | good | | |
| 5. | 1.33 | 500 | 1000 | 4 | 40 | 1.0 | .39 | .39 | good | | |
| 6. | 1.81 | 500 | 1500 | 4 | 40 | .5 | .48 | .96 | good | | |
| 7. | 2.21 | 500 | 2000 | 4 | 40 | .42 | .40 | .955 | good | | |
| 8. | 2.38 | 500 | 2500 | 4 | 40 | .1 | .17 | 1.7 | good | .00284 | |
| 9. | 3.03 | 1000 | 1000 | 4 | 40 | .5 | .65 | 1.3 | good | | |
| 10. | 3.53 | 1000 | 1500 | 4 | 40 | .5 | .5 | 1.0 | good | | |
| 11. | 4.02 | 1000 | 2000 | 4 | 40 | .41 | .49 | 1.2 | good | | |
| 12. | 4.22 | 1000 | 2500 | 4 | 40 | .5 | .2 | .4 | good | | |
| 13. | 4.52 | 1500 | 1000 | 4 | 40 | .33 | .3 | .91 | good | | |
| 14. | 4.71 | 1500 | 1500 | 4 | 40 | .5 | .19 | .38 | good | | |
| | | 1500 | 2000 | 4 | 40 | | | | | | No test. |
| | | 1500 | 2500 | 4 | 40 | | | | | | No test. |

TABLE 5

Bit Number 2991 Z 548 — Type 10 b — Stone Size 10 p. c. — No. Stones in Bit 120 — Total Carats 16.55 — Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water gpm | Water psi | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | .29 | 300 | 1000 | 4 | 40 | .5 | .29 | .58 | good | | |
| 2. | .58 | 300 | 1500 | 4 | 40 | .5 | .29 | .58 | good | | |
| 3. | .85 | 300 | 2000 | 4 | 40 | .5 | .27 | .54 | good | .002925 | |
| 4. | .91 | 300 | 2500 | 4 | 40 | .075 | .06 | .8 | good | | |
| 5. | 1.28 | 500 | 1000 | 4 | 40 | .5 | .37 | .74 | good | | |
| 6. | 1.42 | 500 | 1500 | 4 | 40 | .25 | .14 | .56 | good | | |
| 7. | 1.83 | 500 | 2000 | 4 | 40 | .5 | .41 | .82 | good | | |
| 8. | 2.26 | 500 | 2500 | 4 | 40 | .46 | .43 | .94 | good | .00289 | |
| 9. | 2.58 | 1000 | 1000 | 4 | 40 | .45 | .32 | .71 | good | | |
| 10. | | 1000 | 1500 | 4 | 40 | | | | | | Poor circulation |
| 11. | | 1000 | 2000 | 4 | 40 | | | | | | No test |
| 12. | | 1000 | 2500 | 4 | 40 | | | | | | No test |
| 13. | 2.74 | 1500 | 1000 | 4 | 40 | .16 | .16 | 1.0 | | | Poor circulation |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

TABLE 6

Bit Number 2986 Z 543 Type 15 ab
Stone Size 15 p. c. No. Stones in Bit 120
Total Carats 10.01 Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water | | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | gpm | psi | | | | | | |
| 1. | .15 | 300 | 1000 | 4 | 40 | .5 | .15 | .3 | good | .00291 | |
| 2. | .39 | 300 | 1500 | 4 | 40 | .5 | .24 | .47 | good | | |
| 3. | .61 | 300 | 2000 | 4 | 40 | .5 | .22 | .44 | good | | |
| 4. | .72 | 300 | 2500 | 4 | 40 | .3 | .11 | .37 | good | | |
| 5. | 1.04 | 500 | 1000 | 4 | 40 | .5 | .32 | .64 | good | | |
| 6. | 1.30 | 500 | 1500 | 4 | 40 | .37 | .26 | .70 | good | | |
| 7. | 1.42 | 500 | 2000 | 4 | 40 | .3 | .12 | .40 | good | | |
| 8. | 1.90 | 500 | 2500 | 4 | 40 | .5 | .48 | .96 | good | .00309 | |
| 9. | 2.31 | 1000 | 1000 | 4 | 40 | .5 | .41 | .82 | good | | |
| 10. | 2.56 | 1000 | 1500 | 4 | 40 | .3 | .25 | .83 | good | | |
| 11. | 2.73 | 1000 | 2000 | 4 | 40 | .17 | .17 | 1.0 | | | Poor circulation |
| 12. | | 1000 | 2500 | 4 | 40 | | | | | | Poor circulation |
| 13. | 2.85 | 1500 | 1000 | 4 | 40 | .10 | .12 | 1.2 | | | Poor circulation |
| 14. | | 1500 | 1500 | 4 | 40 | | | | | | No test |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

TABLE 7

Bit Number 2985 Z 542 Type 25 a
Stone Size 25 p. c. No. Stones in Bit 144
Total Carats 8.19 Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water | | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | gpm | psi | | | | | | |
| 1. | .15 | 300 | 1000 | 4 | 40 | .5 | .15 | .3 | good | | |
| 2. | .30 | 300 | 1500 | 4 | 40 | .5 | .15 | .3 | good | .00299 | |
| 3. | .50 | 300 | 2000 | 4 | 40 | .5 | .20 | .4 | good | | |
| 4. | .64 | 300 | 2500 | 4 | 40 | .3 | .14 | .47 | good | | |
| 5. | .99 | 500 | 1000 | 4 | 40 | .5 | .35 | .7 | good | | |
| 6. | 1.35 | 500 | 1500 | 4 | 40 | .5 | .36 | .72 | good | | |
| 7. | 1.73 | 500 | 2000 | 4 | 40 | .47 | .38 | .79 | good | .00297 | |
| 8. | 2.12 | 500 | 2500 | 4 | 40 | .5 | .39 | .78 | good | | |
| 9. | 2.35 | 1000 | 1000 | 4 | 40 | .42 | .23 | .55 | good | | |
| 10. | 2.41 | 1000 | 1500 | 4 | 40 | .17 | .06 | .35 | good | | |
| 11. | | 1000 | 2000 | 4 | 40 | | | | | | Poor circulation |
| 12. | | 1000 | 2500 | 4 | 40 | | | | | | Poor circulation |
| 13. | 2.63 | 1500 | 1000 | 4 | 40 | .17 | .22 | 1.3 | good | | Poor circulation |
| 14. | | 1500 | 1500 | 4 | 40 | | | | | | Poor circulation |
| 15. | | 1500 | 2000 | 4 | 40 | | | | | | Poor circulation |
| 16. | | 1500 | 2500 | 4 | 40 | | | | | | Poor circulation |

TABLE 8

Bit Number 2990 Z 547　　Stone Size 25 p. c.　　Total Carats 6.96
Type 25 b　　No. Stones in Bit 120　　Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water | | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | gpm | psi | | | | | | |
| 1. | .25 | 300 | 1000 | 4 | 40 | .43 | .25 | .58 | good | | |
| 2. | .55 | 300 | 1500 | 4 | 40 | .5 | .3 | .6 | good | | |
| 3. | .81 | 300 | 2000 | 4 | 40 | .5 | .26 | .52 | good | .002965 | |
| 4. | 1.03 | 300 | 2500 | 4 | 40 | .5 | .22 | .44 | good | | |
| 5. | 1.38 | 500 | 1000 | 4 | 40 | .5 | .35 | .7 | good | | |
| 6. | 1.66 | 500 | 1500 | 4 | 40 | .5 | .28 | .56 | good | | |
| 7. | 1.97 | 500 | 2000 | 4 | 40 | .5 | .31 | .62 | good | | |
| 8. | | 500 | 2500 | 4 | 40 | | | | | | No test. |
| 9. | 2.05 | 1000 | 1000 | 4 | 40 | .1 | .08 | .8 | good | .00292 | |
| 10. | 2.42 | 1000 | 1500 | 4 | 40 | .5 | .37 | .74 | good | | |
| 11. | 2.69 | 1000 | 2000 | 4 | 40 | .4 | .27 | .67 | good | | |
| 12. | | 1000 | 2500 | 4 | 40 | | | | | | No test. |
| 13. | | 1500 | 1000 | 4 | 40 | | | | | | No test. |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

TABLE 9

Bit Number 2984 Z 541 Type 40 a
Stone Size 40 p. c. No. Stones in Bit 196
Total Carats 6.03 Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water grm | Water psi | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | .16 | 300 | 1000 | 4 | 40 | .5 | .16 | .32 | good | | |
| 2. | .48 | 300 | 1500 | 4 | 40 | .5 | .32 | .64 | good | | |
| 3. | .64 | 300 | 2000 | 4 | 40 | .34 | .16 | .47 | good | | |
| 4. | .89 | 300 | 2500 | 4 | 40 | .5 | .25 | .5 | good | | |
| 5. | 1.21 | 500 | 1000 | 4 | 40 | .5 | .32 | .64 | good | | |
| 6. | 1.39 | 500 | 1500 | 4 | 40 | .5 | .18 | .36 | good | .00302 | |
| 7. | 1.50 | 500 | 2000 | 4 | 40 | .17 | .11 | .65 | good | | |
| 8. | 1.80 | 500 | 2500 | 4 | 40 | .29 | .3 | 1.0 | good | | |
| 9. | 2.09 | 1000 | 1000 | 4 | 40 | .33 | .29 | .88 | good | | |
| 10. | 2.44 | 1000 | 1500 | 4 | 40 | .33 | .35 | 1.16 | good | .00303 | |
| 11. | 2.66 | 1000 | 2000 | 4 | 40 | .25 | .22 | .88 | good | | |
| 12. | 2.77 | 1000 | 2500 | 4 | 40 | .15 | .11 | .73 | good | | |
| 13. | | 1500 | 1000 | 4 | 40 | | | | | | No test. |
| | | | | | | | | | | | |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

# TABLE 10

Bit Number 2989 Z 546 Stone Size 40 p. c. Total Carats 6.90
Type 40 b No. Stones in Bit 224 Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water | | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | gpm | psi | | | | | | |
| 1. | .13 | 300 | 1000 | 4 | 40 | .33 | .13 | .39 | good | | |
| 2. | .37 | 300 | 1500 | 4 | 40 | .33 | .24 | .73 | good | | |
| 3. | .54 | 300 | 2000 | 4 | 40 | .33 | .17 | .52 | good | | |
| 4. | .73 | 300 | 2500 | 4 | 40 | .33 | .19 | .58 | good | | |
| 5. | .81 | 500 | 1000 | 4 | 40 | .20 | .08 | .4 | good | .00289 | |
| 6. | .89 | 500 | 1500 | 4 | 40 | .10 | .08 | .8 | good | | |
| 7. | .95 | 500 | 2000 | 4 | 40 | .07 | .06 | .86 | good | | |
| 8. | 1.19 | 500 | 2500 | 4 | 40 | .40 | .24 | .6 | good | | |
| 9. | 1.43 | 1000 | 1000 | 5 | 40 | .24 | .24 | 1.0 | good | .002975 | |
| 10. | 1.55 | 1000 | 1500 | 4 | 40 | .12 | .12 | 1.0 | good | | |
| 11. | | 1000 | 2000 | 4 | 40 | | | | | | No test. |
| 12. | | 1000 | 2500 | 4 | 40 | | | | | | No test. |
| 13. | 1.58 | 1500 | 1000 | 4 | 40 | .08 | .03 | .37 | | | Poor circulation |
| 14. | | 1500 | 1500 | 4 | 40 | | | | | | No test. |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

TABLE 11

Bit Number 2983 Z 540 Stone Size 60 p. c. Total Carats 5.33
Type 60 ab No. Stones in Bit 224 Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water gpm | Water psi | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | .20 | 300 | 1000 | 4 | 40 | .33 | .20 | .64 | good | | |
| 2. | .40 | 300 | 1500 | 4 | 40 | .33 | .20 | .64 | good | | |
| 3. | .56 | 300 | 2000 | 4 | 40 | .33 | .16 | .475 | good | .00277 | |
| 4. | .70 | 300 | 2500 | 4 | 40 | .33 | .14 | .42 | good | | |
| 5. | .90 | 500 | 1000 | 4 | 40 | .33 | .20 | .64 | good | | |
| 6. | .99 | 500 | 1500 | 4 | 40 | .15 | .09 | .60 | good | .002985 | |
| 7. | 1.26 | 500 | 2000 | 4 | 40 | .33 | .27 | .82 | good | | |
| 8. | 1.41 | 500 | 2500 | 4 | 40 | .20 | .15 | .75 | good | | |
| 9. | 1.58 | 1000 | 1000 | 4 | 40 | .33 | .17 | .515 | good | | |
| 10. | | 1000 | 1500 | 4 | 40 | | | | | | No test. |
| 11. | | 1000 | 2000 | 4 | 40 | | | | | | No test. |
| 12. | 1.69 | 1000 | 2500 | 4 | 40 | .33 | .11 | .33 | good | | |
| 13. | 1.75 | 1500 | 1000 | 4 | 40 | .23 | .06 | .26 | good | | Poor circulation |
| 14. | | 1500 | 1500 | 4 | 40 | | | | | | No test. |
| | | | | | | | | | | | |
| | | | | | | | | | | | |

TABLE 12

Bit Number 2982 Z 539 Stone Size 100 p. c. Total Carats 4.43
Type 100 a No. Stones in Bit 252 Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water | | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | grm | psi | | | | | | |
| 1. | .08 | 300 | 1000 | 4 | 40 | .33 | .08 | .24 | good | | |
| 2. | .18 | 300 | 1500 | 4 | 40 | .33 | .1 | .3 | good | .00280 | |
| 3. | .35 | 300 | 2000 | 4 | 40 | .33 | .17 | .515 | good | | |
| 4. | .58 | 300 | 2500 | 4 | 40 | .33 | .23 | .7 | good | | |
| 5. | .65 | 500 | 1000 | 4 | 40 | .13 | .07 | .54 | good | | |
| 6. | .75 | 500 | 1500 | 4 | 40 | .17 | .10 | .59 | good | | |
| 7. | .97 | 500 | 2000 | 4 | 40 | .27 | .22 | .82 | good | .00284 | |
| 8. | 1.21 | 500 | 2500 | 4 | 40 | .33 | .24 | .73 | good | | |
| 9. | 1.30 | 1000 | 1000 | 4 | 40 | .10 | .09 | .9 | good | | Poor circulation. |
| 10. | | 1000 | 1500 | 4 | 40 | | | | | | No test. |
| 11. | | 1000 | 2000 | 4 | 40 | | | | | | No test. |
| 12. | | 1000 | 2500 | 4 | 40 | | | | | | No test. |
| 13. | 1.43 | 1500 | 1000 | 4 | 40 | .33 | .13 | .39 | good | | |
| 14. | | 1500 | 1500 | 4 | 40 | | | | | | No test. |
| 15. | | 1500 | 2000 | 4 | 40 | | | | | | No test. |
| | | | | | | | | | | | |

TABLE 13

Bit Number 2988 Z 545 — Type 100 b — Stone Size 100 p. c. — No. Stones in Bit 224 — Total Carats 3.82 — Rock Type Dolomite

| No. | Cumulative feet drilled | Bit Pressure | r.p.m. | Water gpm | Water psi | Drill time Min. | Feet Drilled | Rate of Advance ft/min. | Bit Condition after test | Size of cuttings | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | .33 | 300 | 1000 | 4 | 40 | .33 | .10 | .3 | good | | |
| 2. | .55 | 300 | 1500 | 4 | 40 | .33 | .22 | .67 | good | .00280 | |
| 3. | .74 | 300 | 2000 | 4 | 40 | .33 | .19 | .58 | good | | |
| 4. | .89 | 300 | 2500 | 4 | 40 | .33 | .15 | .455 | good | | |
| 5. | .92 | 500 | 1000 | 4 | 40 | .14 | .03 | .21 | good | .00273 | |
| 6. | 1.00 | 500 | 1500 | 4 | 40 | .17 | .08 | .47 | good | | Poor circulation. |
| 7. | | 500 | 2000 | 4 | 40 | | | | | | No test. |
| 8. | | 500 | 2500 | 4 | 40 | | | | | | No test. |
| 9. | | 1000 | 1000 | 4 | 40 | | | | | | No test. |
| 10. | | 1000 | 1500 | 4 | 40 | | | | | | No test. |

# BIBLIOGRAPHY

Books:

Cumming, J. D. Diamond drill handbook. J. K. Smit & Sons, of Canada Ltd., 1951.

Grodzinski, P. Diamond tools. N. Y., A. Smit & Co., Inc., 1944. 379 p.

Periodicals:

Adamson, P. Drilling trends. Mining World, Vol. 9, pp. 24-26, March, 1947.

Adamson, P. What goes on in the diamond drill hole. Engineering and Mining Journal, September, 1946.

Hanifen, J. African bort attains increasing use in diamond drilling. Engineering and Mining Journal, Vol. 131, pp. 75-76, January, 26, 1931.

Hansen, Meyer G. Diamond drill practice on the Mother-Lode. Mining Congress Journal, Vol. 21, pp. 35-37, January, 1935.

Hopper, C. H. Diamond core bits at Matachewan Consolidated Mines Ltd., Matachewan, Ontario. Canadian Mining Journal, Vol. 60, pp. 600-601, October, 1939.

Raney, A. F. Development of modern diamond drill bit; many considerations affect selection and setting of stones. Canadian Mining Journal, Vol. 61, pp. 796-803, December, 1940.

Rockwell, F. G. Industrial diamonds. Mining and Metallurgy, Vol. 25, pp. 257-259, May, 1944.

Sanderson, L. Rock drilling with diamonds. Colliery Engineering, Vol. 17, pp. 94-96, April, 1940.

Storms, W. R. Diamond drill bits and carbon. Engineering and Mining Journal, Vol. 134, pp. 96-98, March, 1933.

Williams, N. Diamond bit coring at Rangley. Oil and Gas Journal, Vol. 46, pp. 141-142, 173-175, October 11, 1947.

Young, G. J. Setting diamonds in drill bits. Engineering and Mining Journal, Vol. 115, pp. 576-577, March, 1923.

Anon. How to use diamond bits in deep drilling. Petroleum Engineer, Vol. 19, pp. 179, 182, 184 and 186, September, 1948.

Anon. Use and care of diamond drill bits and shells. Engineering and Mining Journal, Vol. 148, pp. 78-81, August, 1947.

Publications of Learned Societies:

Armstrong, L. C. Diamond drilling quartz-feldspar intergrowths. American Institute of Mining and Metallurgical Engineers. Mining Transactions. Vol. 184, pp. 177-178, June, 1949.

Blake, Rolland Laws. The cutting action of a diamond bit. University of Minnesota. Master of Science thesis. October, 1951.

Hopper, C. H. The engineer and the diamond drill in Northern Ontario. Canadian Institue of Mining and Metallurgical Engineers. Transactions. December, 1943.

Kendrick, W. L. Drilling and blasting. University of Minnesota Center of Continuation Study. February, 1942.

Longyear, R. D. New diamond drilling practice in the United States. Canadian Diamond Drilling Association. Procedures. June 7, 1947.

Sundberg, K., and Lindquist, O. Some recent developments in diamond drilling practice. Institute of Mining and Metallurgy. Bulletin, no. 402. March 10, 1938.

Westman, Burton J. Discussion-"Diamond drilling of quartz-feldspar intergrowths", by L. C. Armstrong. American Institute of Mining and Metallurgical Engineers. Mining Transactions. Vol. 182, November, 1950.

U. S. Government Publications:

Long, Albert. Diamond orientation in diamond bits, procedures and preliminary results. U. S. Bureau of Mines. Report of Investigations 4800, June, 1951.

Long, Albert. Effects of core recovery, diamond size, and quality on cost of core drilling in gneiss. U. S. Bureau of Mines. Report of Investigations 4628, January, 1950.

Obert, L. and others. Diamond drilling and diamond bit investigations. U. S. Bureau of Mines. Report of Investigations 4041, March, 1947.

Obert, L. and others. Diamond drilling and diamond bit investigations, part 2. Tests on cost-set coring bits. U. S. Bureau of Mines. Report of Investigations 4233, April, 1948.

# VITA

Robert John Michael Miller, son of William Martin and Ruth Margaret Miller, was born at Mercer, Wisconsin, on March 27, 1928. He attended the public schools of Mercer, Wausau, and Hurley, Wisconsin.

From May, 1945 to August, 1946 he served in the U. S. Navy.

He matriculated at the Wisconsin Institute of Technology, Platteville, Wisconsin in September, 1946 and was graduated with a Certificate in Mining Engineering in May, 1949. He entered the Missouri School of Mines and Metallurgy in September, 1949 and was graduated in June, 1950 with a Bachelor of Science Degree in Mining Engineering, Mining-Geology Option. He began graduate studies at Missouri School of Mines and Metallurgy in September, 1950 as a Graduate Assistant and became an Instructor in Mining Engineering in January, 1951.

He has worked summers for five different mining companies throughout the United States doing various jobs ranging from mining to engineering.