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"A DRILLABILITY CLASSIFICATION OF GEOLOGICAL FORMATIONS"

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THIS THESIS IS
DEDICATED TO MY WIFE
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A DRILLABILITY CLASSIFICATION
OF GEOLOGICAL FORMATIONS*

BY
ALBERT LEE HEAD, JR.

ABSTRACT

THIS THESIS HAS BEEN WRITTEN BECAUSE OF THE NEED IN THE OIL WELL DRILLING INDUSTRY FOR A SYSTEM BY WHICH DIFFERENT TYPES OF BITS CAN BE CLASSIFIED WITH RESPECT TO DIFFERENT TYPES OF GEOLOGICAL FORMATIONS.

AS BACKGROUND MATERIAL, A DISCUSSION OF THE FACTORS WHICH AFFECT THE RATE OF PENETRATION OF ROCK BITS HAS BEEN PRESENTED. THESE FACTORS ARE: (1) FORMATION, (2) TYPE OF BIT, (3) WEIGHT ON BIT, (4) ROTATIONAL SPEED, (5) HYDRAULIC ACTION, (6) SIZE OF HOLE, AND (7) PERSONNEL AND EQUIPMENT.

A CLASSIFICATION OF GEOLOGICAL FORMATIONS BASED ENTIRELY UPON THE RELATIVE EFFICIENCY WITH WHICH THESE FORMATIONS CAN BE DRILLED WITH A SMALL ROLLING-CUTTER TYPE OF TEST BIT HAS BEEN ESTABLISHED. THIS CLASSIFICATION HAS BEEN SHOWN TO BE CONSISTENT WITH ACTUAL FIELD DRILLING PRACTICES.

A METHOD OF CLASSIFYING DIFFERENT TYPES OF ACTUAL BITS WITH RESPECT TO THE CLASSIFIED FORMATIONS HAS BEEN ILLUSTRATED. THIS METHOD

* A PAPER BASED ON THIS THESIS HAS BEEN ACCEPTED FOR PRESENTATION AT THE THIRD WORLD PETROLEUM CONGRESS, THE HAGUE, HOLLAND, MAY 28—JUNE 6, 1951. THIS PAPER WITH DISCUSSIONS WILL BE PUBLISHED IN THE PROCEEDINGS OF MASTER SECTION 2 OF THE CONGRESS.
PROVIDES A MEANS OF DETERMINING A SPHERE OF APPLICATION FOR EACH TYPE OF BIT; THAT IS, THE FORMATIONS WHICH EACH TYPE DRILLS MOST ECONOMICALLY WITH RESPECT TO ALL THE OTHER TYPES CAN BE DETERMINED. THIS MEANS THAT MOST OF THE GUESSWORK CONCERNING THE SELECTION OF A BIT FOR A PARTICULAR FORMATION CAN BE ELIMINATED.

LIMITED TESTS HAVE BEEN CONDUCTED TO DETERMINE IF THERE IS ANY RELATIONSHIP BETWEEN THE DRILLABILITY OF A FORMATION AND THE HARDNESS. BASED ON THE RESULTS OF THESE TESTS, NO RELATIONSHIP COULD BE ESTABLISHED.
INTRODUCTION

Perhaps the major problem which confronts the oil well drilling industry is that of the selection of the proper type of drilling bit for any particular application. A knowledge of the relative merits of any type of drilling bit would be exceedingly valuable to drillers and bit manufacturers alike. To provide a procedure by which these merits can be determined, "A Drillability Classification of Geological Formations" is hereby proposed.

What is a drillability classification of geological formations, and what is its relationship to the over-all problem of improving oil well drilling practices? A drillability classification of geological formations is a classification based upon the relative efficiency with which formations can be drilled. The purpose of such a classification is to provide a scale by which different types of drilling bits can be compared with each other with respect to geological formations. This system would eliminate much of the guesswork associated with the selection of a drilling bit for any particular formation. At this time, each driller has his own ideas, based upon his experience, concerning the selection of a particular type of bit for a particular formation. The individual driller may be either right or wrong; however, a survey of the opinions of many drillers has resulted in a general trend which classifies a bit either as a hard formation bit or as a soft formation bit. Yet, there is still much latitude concerning the selection of a bit, because there are many types of hard and soft formation bits. The establishment of a drillability classification of geological formations would be a step towards classifying bits with respect to formations.
THEY DRILL MOST EFFICIENTLY.

Since the efficiency with which a formation can be drilled is manifested by the rate of penetration of the drilling bit in the formation, a study of the factors which affect the rate of penetration is in order. Many investigators have heretofore studied and analyzed the factors which affect the rate of penetration. The objective of this investigation will not be to duplicate these many noteworthy reports; but since there is a close relationship between the rate of penetration and the establishment of a drillability classification, a summary of these factors will be given.
A SUMMARY OF FACTORS WHICH AFFECT THE
RATE OF PENETRATION OF ROCK BITS

The importance of the rate of penetration has long been recognized by the oil well drilling industry. The cost of actually drilling a well is approximately 75 per cent of the total cost of the well; moreover, most of the drilling costs are dependent on the time element. Any method of increasing the rate of penetration, therefore, will reduce the time element and decrease the cost of drilling. A thorough understanding of the factors which affect the rate of penetration is essential before methods of increasing this rate can be developed. These factors are:

1. Formation
2. Type of Bit
3. Weight on Bit
4. Rotational Speed
5. Hydraulic Action
6. Size of Hole
7. Efficiency of Personnel and Equipment

FORMATION: The geological formation encountered is the only factor truly independent of control. Some of the more common formations drilled are shale, sticky shale, salt, plastic clay, sandy shale, soft sand, sand, gravel, hard sand, sandstone, limestone, hard limestone, dolomite, and granite. Each formation has characteristics which affect its resistance to penetration; hence, the disposition of the remaining

(a) Numeral superscripts refer to BIBLIOGRAPHY.
FACTORS MUST BE OF SUCH A MANNER TO PRODUCE THE MAXIMUM ECONOMICAL RATE OF PENETRATION.

**TYPE OF BIT:** The rock bit is the instrument which transmits energy to the formation being drilled. Since the rate of penetration is necessarily dependent on the amount of energy applied and the manner of application, the importance of efficient energy transmittal cannot be ignored. A theoretical and scientific investigation of the rock bit design problem is virtually an impossibility because of the numerous unknown variables; so, the design of rock bits has been based upon empirical considerations which seem to indicate increased penetration rates.

The cutting elements of rock bits are of two general forms; one is cylindrical, and the other is conical. On these cutting elements are formed teeth of various designs. The angle formed between the intersection of the cutter axis and a plane containing the longitudinal axis of a tooth varies from 0 to 90 degrees. As the cutter rotates each tooth successively strikes the formation, delivering sharp impacts. In hard, brittle formations high compressive stresses are induced around each point of impact. If these induced stresses exceed the ultimate crushing strength, the formation will be removed by a chipping action similar to that of a sculptor's chisel. In relatively soft formations the teeth will embed themselves as the cutter rotates, producing wedging actions which pry the formation loose.

Rock bit manufacturers have constantly endeavored to improve their bits; however, the fundamental design of bits has changed very little. Metallurgical advancements are responsible for most bit improvements.
Superior alloys have been developed; heat treatment techniques have been perfected; and areas subject to severe abrasion have been dressed with tungsten carbide. The general tendency, concerning the tooth pattern on cutters, is to have shallow, closely spaced teeth for hard formations and deep, widely spaced teeth for soft formations. There are innumerable tooth patterns manufactured which display no better cutting performance than some slightly different pattern, the difference being only a matter of opinion.

Concerning the bit, more study should be applied to the actual cutting elements to effectuate increased penetration rates. These cutting elements need to be designed to facilitate the removal of the cuttings by the drilling fluid more effectively.

Weight on bit: The weight applied on the bit has been found to have a most significant effect upon the rate of penetration. The fact that penetration rates increase with increased bit weights is well known; yet, the exact manner of the variation has not been conclusively determined.

Tests have been conducted to evaluate the effect of bit weight upon penetration rate. During these tests all other factors affecting the rate of penetration were kept constant. The weight was varied between 10,000 pounds and 30,000 pounds, and the fluid circulation was sufficient to keep the bit clean at all weights. In hard, dense formations with approximate penetration rates of 5 to 12 feet per hour, the penetration rate was directly proportional to the bit weight. Actually, some deviation from direct proportionality occurred; nevertheless, the relationship can be taken as an effective average value.
In medium hard, abrasive formations with approximate penetration rates of 10 to 40 feet per hour, a 100 per cent increase of weight resulted in a penetration rate increase of 55 per cent.3

In softer formations with approximate penetration rates of 50 to 90 feet per hour, a 100 per cent increase of weight resulted in a penetration rate increase of 50 per cent.3,4

Retrospectively, an increase of weight is more effective in hard formations than in soft ones; however, there is a most economical weight for any set of conditions. Other tests which consider the life of the bit indicate that the weight which produces the maximum rate of penetration is not the optimum weight to use.5 The optimum weight for hard formation drilling is approximately 25,000 pounds for a cross cutter type of bit 6-3/4 inches in diameter. Although this value is about half of the value which produces maximum penetration rates, the total footage drilled per bit is almost 300 per cent greater than the total footage obtained when using the maximum weight. Excessive wear and unusually high stresses in the bit are produced when the weight for maximum penetration rate is applied, resulting in premature failure of the bit.

Obviously, there are upper and lower limits beyond which weight variations produce no change of penetration rates. The lower limit is the weight necessary to cause the compressive strength of the formation to be exceeded as each tooth strikes it. Unless the minimum weight is applied, the formation is merely worn away. When the minimum weight or some greater weight is applied, the formation will be chipped away. The upper limit is the weight which causes the maximum rate of penetra-
ROTATIONAL SPEED: Of the factors which affect the rate of penetration, the rotational speed is probably the most controversial. Speeds of 40 to 400 revolutions per minute are in common use at this time, and speeds as high as 750 revolutions per minute have been used for experimental drilling. The selection of the rotational speed has depended primarily upon the drillers' opinion, founded upon their experience, rather than upon the formation being drilled.

In general, other factors remaining constant, the rate of penetration increases as the rotational speed increases, assuming the fluid circulation is adequate to remove the cuttings. There is an exception to this general postulation, however. Hard formations such as limestones, quartzite, anhydrite, and sandstones are best drilled using rotational speeds of 40 to 100 revolutions per minute. These formations cannot be drilled at high rotational speeds because of the physical limitations imposed by the drilling equipment. At high speeds severe vibrational conditions exist which cause premature failure of the drill pipe.

Specifically, the results of one investigation showed that over a period of 45 months the rate of penetration increased 39.6 per cent because of a rotational speed increase of 33-1/3 per cent — 75 to 100 revolutions per minute. Another study, limited to bits having two cutting elements drilling Taylor shale, revealed that the rate of penetration increased 50 per cent when the rotational speed increased 100 per cent.


TESTS HAVE BEEN PERFORMED TO EVALUATE THE EFFECT OF THE CIRCULATION RATE UPON THE PENETRATION RATE. ONE SUCH TEST REVEALED AN AVERAGE PENETRATION RATE INCREASE OF 28.6 PER CENT FOR EACH 200 GALLONS PER MINUTE INCREASE OF CIRCULATION RATE. More recent tests confirm the general trend that an increase of circulation rate results in an increase of penetration rate; however, the increase of penetration rate is small compared to the increase of hydraulic horsepower necessary to effectuate the change. In all instances the annular return velocity must be sufficient to remove the cuttings. A return velocity of 200 FEET PER MINUTE HAS BEEN USED SUCCESSFULLY BY ONE INVESTIGATOR.
Until recent years the nozzle-fluid velocity has been given little consideration. Experiments performed to evaluate the nozzle-fluid velocity effect have shown it to be of significance. These experiments indicate that the penetration rate increases as the velocity increases, assuming the annular return velocity is sufficient to remove the cuttings. In medium hard formations the penetration rate of two-cutter jet bits changes little if velocities less than 150 feet per second are used. Between velocities of 150 and 200 feet per second, a distinct increase in the rate of penetration usually occurs; however, from this point on, the rate of increase of the rate of penetration decreases as the velocity increases.

Based on the most reliable sources available, the penetration rate increases as the velocity increases when all of the fluid is directed on the bottom of the hole. Too, there is a minimum nozzle-fluid velocity for each formation, below which the rate of penetration is not significantly affected by variation of the fluid velocity.

The nozzle efficiency directly affects the hydraulic horsepower necessary to maintain adequate rate of circulation and nozzle-fluid velocity. The coefficient of discharge of commonly used bit nozzles varies between 0.80 and 0.92. Therefore, the use of more efficient nozzles will make available additional horsepower for increasing the rate of penetration. For example, a change in the nozzle coefficient of discharge from 0.80 to 0.99 will reduce the pressure drop and horsepower loss as the nozzle approximately 35 per cent. 4

Size of Hole: Differences of opinion exist concerning the proper size of hole to drill. Comparison of rates of penetration obtained
WITH DIFFERENT SIZED BITS SHOWS NO DEFINITE TREND. THE RATE OF PENE-
TRATION SHOULD, THEORETICALLY, INCREASE AS THE HOLE DIAMETER IS REDUCED;
but this does not always happen. SMALLER BITS MUST BE RUN WITH LIGHTER
LOADS THAN LARGE BITS; THE NET RESULT, IN MANY CASES, IS PENETRATION
RATES THAT ARE ABOUT EQUAL. CONSEQUENTLY, THE SELECTION OF THE HOLE
SIZE IS USUALLY BASED UPON ECONOMIC CONSIDERATIONS.

EFFICIENCY OF PERSONNEL AND EQUIPMENT: CERTAINLY, THE EFFICIENCY
OF PERSONNEL AND EQUIPMENT HAS THE GREATEST EFFECT UPON THE RATE OF PENE-
TRATION OF ROCK BITS. AN INVESTIGATION EXTENDING OVER A THREE-YEAR
PERIOD SHOWS THAT THE RATE OF PENETRATION INCREASED 55.5 PER CENT AS A
RESULT OF INCREASED EFFICIENCY OF PERSONNEL AND EQUIPMENT.3

THE EFFECT OF PERSONNEL EFFICIENCY HAS BEEN ILLUSTRATED FURTHER AS
A RESULT OF THE RECENT WAR. DURING THE PERIOD OF 1942 TO 1944 THERE
WAS AN ACTUAL DECLINE IN THE RATE OF PENETRATION.7 APPARENTLY, THE
ONLY CHANGE TO CAUSE THIS DECLINE WAS THE LOSS OF EXPERIENCED PERSONNEL
to the armed services. THESE MEN WERE REPLACED BY MEN WITH LESS EXPERI-
ENCE, RESULTING IN DECREASED DRILLING EFFICIENCY.
ESTABLISHMENT OF A DRILLABILITY CLASSIFICATION

As evidenced by the preceding discussion, there are many factors which affect the rate of penetration of a bit. Also, general agreement exists among most drillers and manufacturers concerning the manner in which these factors tend to affect the rate of penetration. The aim of all the former investigators has been to devise means of making oil well drilling more economical by increasing the rate of penetration; however, the majority of these investigators have presupposed that the proper type of drilling bit was being used in the particular formation being drilled. A so-called hard formation bit was employed in a hard formation, to be sure; but since many types of hard formation bits exist, perhaps a slightly different type of bit would have performed better. Very little, if any, research has been done to establish as closely as possible a definite sphere of application for each type of bit. Consequently, many types of bits probably have overlapping spheres of application; indeed, they may have coincident spheres of application. Thus, the need for a system whereby different types of bits are classified in a relative manner with respect to formations drilled is of great importance.

One method of classifying bits with respect to formations drilled would be to systematically test each type of bit in every formation. By varying the remaining factors which affect the rate of penetration, each type would be found to drill in some one formation more economically than in all the other formations. Obviously, such a system of classifying bits would be impractical, if not impossible, because of the tremendous financial costs that would be required.
As a means to an end, another method of classifying bits would be first to classify the formations with respect to each other and then to classify the different types of bits with respect to the classified formations. A drillability classification of geological formations, as described in the introduction, would adequately classify the various formations with respect to each other. Once a drillability classification has been established, each type of bit could be graded in accordance with its performance in each formation — the performance of each bit being determined by observation of actual field and experimental drilling data over a long period of time. In each formation there would be one type which would distinguish itself above all the others. If two or more bits performed equally well, they would have overlapping spheres of application; and one of them should be eliminated. Hence, a schedule of bits showing which formations they drill best could be prepared.

The primary objective of this thesis will be to establish a drillability classification of geological formations. This classification will be limited to formations commonly referred to as hard formations which are drilled with a rolling-cutter type of bit.

A method of classifying different types of bits with respect to the classified formations will be illustrated; however, the problem of actually classifying different bits will be left for a future study.

Apparatus: To determine a drillability classification, an instrument of some type needed to be designed. The function of this instrument would be to classify geological formations in a relative manner with respect to the efficiency with which these various formations
could be drilled. Furthermore, the results obtained with this instrument must be consistent with the results obtained from actual bits drilling these same formations under field conditions.

To fulfill the preceding requirements, the obvious type of instrument to design would be a bit. Formation samples are available in the form of core samples; so, the diameter which this test bit drills must be made small enough to enable the bit to drill in core samples of common sizes. Since the vast majority of hard formations are actually drilled with rolling-cutter types of bits, the test bit should be a rolling-cutter type of bit to obtain drilling action similar to that of an actual bit.

In conformity with functional requirements of the test bit and experience gained by the author in the bit manufacturing business, a small test bit has been designed and made. This bit is shown in Figure 1. The diameter of the hole that the test bit drills is 2 inches. There are two cylindrical cutters each of which has a diameter of 1 inch. On one cutter, 13 teeth are formed with a helix angle of 30 degrees left hand. On the other cutter, 14 teeth are formed with a helix angle of 15 degrees right hand. A different number of teeth on each cutter and opposite helix angles are necessary to prevent tracking of the cutters. The test bit was designed to facilitate the replacement of the cutters after each drillability test. The journals around which the cutters rotate are held in place by small set screws. By loosening the set screws, the journals can be removed easily, and the cutters will then drop out.

(b) Figures follow the bibliography.
The test bit will not drill the center portion of the hole. It was designed that way to eliminate the inefficient cutting action which occurs at the center. A small diamond core bit which drills a diameter of 1-3/8 inches has been made to drill out the center portion of the hole prior to drillability tests made with the test bit; this bit is shown in Figure 2.

For the test bit to drill a formation, there must be an axial force applied to the bit while either the bit or the formation rotates. Many mechanisms which would provide this combination of force and rotation could be designed; however, a lathe with a few simple alterations would satisfactorily fulfill the requirements. A lathe was modified and used as the drillability test apparatus.

By means of a threaded connection, the test bit was secured to the spindle of an adapter which in turn was mounted in the tailstock of the lathe. (The formation sample was held in the chuck of the lathe.) The adapter was made from a live center. The spindle of the live center was removed, and another spindle was made with a female threaded connection turned on the end. This threaded connection was a 1"-14NF-3 shouldered connection. The spindle was designed so that it would rotate freely. Thrust bearings were installed to absorb axial loads applied. Directly behind the threaded connection on the spindle was attached a 6 inch lever arm with which rotational movement of the spindle could be restrained. Torque applied to the spindle could be determined by measurement of the force on the 6 inch lever arm necessary to restrain the rotation of the spindle.

Axial force was applied to the bit by turning the tailstock screw.
In order to exert a constant axial force on the bit, a constant torque must be applied to the tailstock screw. To do this, a small drum was made to replace the tailstock hand wheel which turns the tailstock screw. A small wire cable was wound on the drum and threaded through a pulley located above the drum. A container for holding weights was attached to the free end of the cable. For any weight placed in the container, a constant force would be exerted by the bit.

A deflection scale was designed, as shown in Figure 3, to measure directly the force exerted by the bit for any particular weight placed in the container. This scale consists of two identical, short cantilever beams fixed to a common base and located a short distance apart. A dial indicator is mounted between the beams to measure deflection of the beams. The scale was designed to withstand a maximum load of 500 pounds applied on load points located near the ends of the beams. For this maximum load, the theoretical deflection between the beams is 0.055 inch. With the use of a Southwart-Emery Testing Machine, the scale was calibrated. The calibration curve is shown in Figure 4.

Using the deflection scale, the drillability test setup was calibrated. This calibration curve of cable load versus axial bit thrust is shown in Figure 5. Knowing the physical characteristics of the tailstock screw and the drum, theoretical curves of cable load versus axial bit thrust were drawn for three different values of coefficient of friction for the tailstock screw. This was done as a matter of interest. These theoretical curves were plotted on the same coordinates as the actual calibration curve. (See Figure 5.) The coefficient of friction of the tailstock screw reflected by the actual curve is approxi-
Mately 0.26, a reasonable value for this application.

The axial movement of the bit can be accurately determined by noting the length of cable wound off the drum. The physical characteristics of the tailstock screw and drum magnify the axial movement of the bit approximately 125 to 1; for example, if the cable unwinds \(\frac{1}{8}\) inch, the bit moves axially \(\frac{1}{1000}\) inch.

With the apparatus described above, as shown assembled in Figure 6, measurements of rotational speed, force exerted by the bit, torque, the depth drilled by the bit, and time necessary to drill the depth can be taken.

**Test Procedure:** Before tests were made to establish a drillability classification, preliminary tests were made to observe the performance of the test bit. Tests were run in very hard formations and in relatively soft formations. For a very hard formation, a core sample of West Texas Chert was used. There was no difficulty encountered in holding this sample in the chuck of the lathe. A number of tests were run in this chert to determine the durability of the cutters. For a depth of \(1\frac{1}{4}\) inch, the wear of the cutters was excessive. Wear appeared to be negligible for depths under \(\frac{1}{8}\) inch. To determine the performance of the test bit in this sample of chert, the rate of penetration was determined for different values of bit thrust while the rotational speed remained constant. The results of these runs are shown plotted in Figure 7. The rate of penetration was found to be directly proportional to the bit thrust for a given rotational speed. Other investigators have also found the rate of penetration to be directly proportional to the weight applied to actual rock bits.\(^2, 3, 4\) Therefore, the performance of the
TEST BIT IS SIMILAR TO THE PERFORMANCE OF ACTUAL ROCK BITS.

In relatively soft formations such as salt and unconsolidated sandstones, several difficulties were encountered. The samples were difficult to mount in the chuck. Under each jaw of the chuck the sample would crumble away, allowing the sample to move. To remedy this situation, a thin, soft wood strip was placed between each jaw and the sample. This prevented the jaws from digging into the sample. However, there was another difficulty. If the sample was very unconsolidated, it would merely crumble apart when the bit was applied to it. Nothing could be done to remedy this difficulty. Formations of this character had to be excluded from the tests. No rules can be postulated which will determine whether or not a formation is capable of being drilled. The only criterion is to try and see.

To establish a drillability classification with the described test apparatus, the core sample was mounted in the chuck of the lathe; the center was drilled out with the diamond core bit; and the test bit was then run on the sample. Figures 8 and 9 represent these operations pictorially. Perhaps the major problem encountered was that of deciding what factors to compare to establish a relative classification of the formations. If a series of tests were made in each formation similar to the tests made in West Texas Chert, shown in Figure 7, the problem of what to compare would still exist. The family of curves obtained would be shifted one way or the other along the rate of penetration axis. Nothing specifically could be compared.

The work required to drill a certain depth in each sample could be determined by taking measurements of torque and time. However, accurate
TORQUE MEASUREMENTS WERE IMPOSSIBLE TO OBTAIN BECAUSE OF VIBRATIONAL CONDITIONS INHERENT FOR THIS TYPE OF TEST. FURTHERMORE, ON THE BASIS OF TORQUE MEASUREMENTS OBTAINED FOR SEVERAL FORMATIONS AT DIFFERENT CONDITIONS OF ROTATIONAL SPEED AND BIT THRUST, THE RANGE OF TORQUE READINGS WAS NOT SUFFICIENTLY BROAD BETWEEN FORMATIONS RELATIVELY EASY TO DRILL AND FORMATIONS RELATIVELY HARD TO DRILL. FOR EXAMPLE, THE TORQUE MEASUREMENT IN MISSISSIPPI LIME, A FORMATION WHICH IS RELATIVELY EASY TO DRILL, WAS 42 INCH-POUNDS WHEREAS THE MEASUREMENT IN QUARTZIFEROUS SANDSTONE, A FORMATION WHICH IS HARD TO DRILL, WAS ONLY 63 INCH-POUNDS.


AS STATED PREVIOUSLY, THE WEAR ON THE CUTTERS WAS NEGLIGIBLE FOR DEPTHS UNDER 1/8 INCH. THEREFORE, A DEPTH OF 1/16 INCH WAS SELECTED AS THE DEPTH TO BE USED FOR THE DRILLABILITY CLASSIFICATION TESTS. BECAUSE NEGLIGIBLE WEAR ON THE CUTTERS, A WIDE RANGE OF TIME VALUES WAS FOUND FOR THIS DEPTH. THE PROCEDURE WAS TO START THE DRILLABILITY TEST ON A SAMPLE, LET THE BIT DRILL IN FOR 1/16 INCH, AND THEN TIME THE SECOND 1/16 INCH DRILLED. THIS PROCEDURE ASSURED UNIFORM STARTING CONDITIONS FOR EACH TEST.
In conjunction with the selection of the depth to be drilled, the speed and bit thrust had to be chosen. A rotational speed of 110 revolutions per minute was used. This was a convenient speed on the lathe, the nearest other speeds being 60 and 188 revolutions per minute. Also, at 110 revolutions per minute, the drilling action of the bit was most uniform over the range of formations to be drilled. A bit thrust sufficient to produce chipping action on all formations was necessary. For this thrust, a value of 417 pounds was sufficient; that is, in each formation the bit thrust would be beyond the point at which chipping action begins. This value was determined actually by trial and error.

With the depth and rotational speed being fixed at the above values, this value of bit thrust was selected on the basis of time values and chipping action obtainable over the range of formations to be drilled.

Thus, to determine a drillability classification of geological formations, the time intervals necessary to drill 1/16 inch in each formation were compared, the rotational speed of 110 revolutions per minute and the bit thrust of 417 pounds remaining constant. These time intervals measured in seconds were called the Drillability Classification Numbers of the formations tested.

Test results: The drillability test bit was run in 15 different formations which are commonly encountered in oil well drilling. Each formation was tested as described in the preceding section. The Drillability Classification Number established for each formation is the average result of at least two tests. In several instances, it is the average result of three tests. The results of all the tests are shown in Table 1.
TABLE 1

Test data used to determine Drillability Classification Numbers. Bit thrust, rotational speed, and depth drilled were held constant at 417 pounds, 110 revolutions per minute, and 1/16 inch, respectively.

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>LOCATION</th>
<th>TIME (MIN-SEC)</th>
<th>AVERAGE RATE OF PENETRATION (FT/HR)</th>
<th>DCNc</th>
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<tr>
<td>SANDSTONE, Wilcox</td>
<td>Natchez, Miss.</td>
<td>0-2.0</td>
<td>9.88</td>
<td>1.9</td>
</tr>
<tr>
<td>LIME, Canyon Reef</td>
<td>Snyder, Tex.</td>
<td>0-2.0</td>
<td>9.38</td>
<td>2.0</td>
</tr>
<tr>
<td>ANHYDRITE</td>
<td>Gulf Coast Tex.</td>
<td>0-4.1</td>
<td>5.52</td>
<td>3.4</td>
</tr>
<tr>
<td>LIME, Mississippi</td>
<td>Dover, Okla.</td>
<td>0-4.0</td>
<td>4.82</td>
<td>3.9</td>
</tr>
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<td>HARD MARINE SHALE, Hosston</td>
<td>Haynesville, La.</td>
<td>0-4.7</td>
<td>4.37</td>
<td>4.3</td>
</tr>
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<td>CRYSSTALLINE LIME</td>
<td>Rotan, Tex.</td>
<td>0-12.0</td>
<td>1.62</td>
<td>11.6</td>
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<td>CARBONIFEROUS SHALE</td>
<td>West Tex.</td>
<td>0-16.1</td>
<td>1.25</td>
<td>15.0</td>
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<td>HARD SANDSTONE, First Bromide</td>
<td>Lindsey, Okla.</td>
<td>0-21.2</td>
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<td>19.6</td>
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<td>SANDY LIMESTONE, Smackover</td>
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<td>26.0</td>
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<td>SANDSTONE</td>
<td>Unknown</td>
<td>0-38.4</td>
<td>0.503</td>
<td>37.3</td>
</tr>
<tr>
<td>SYENITE</td>
<td>Central Tex.</td>
<td>0-38.4</td>
<td>0.497</td>
<td>37.7</td>
</tr>
<tr>
<td>CHERT</td>
<td>West Tex.</td>
<td>0-47.0</td>
<td>0.408</td>
<td>45.8</td>
</tr>
<tr>
<td>PINK GRANITE</td>
<td>Central Tex.</td>
<td>1-15.0</td>
<td>0.253</td>
<td>74.1</td>
</tr>
<tr>
<td>QUARTZIFEROUS SANDSTONE, Hosston</td>
<td>Bethany, Tex.</td>
<td>9-39.6</td>
<td>0.034</td>
<td>555.7D</td>
</tr>
</tbody>
</table>

(c) Drillability Classification Number.
(d) This formation was very hard, consolidated, abrasive sandstone which could not be chipped regardless of the thrust applied to bit. For this reason the DCN is exceedingly high.
A DRILLABILITY CLASSIFICATION HAS BEEN ESTABLISHED FOR THE ABOVE FORMATIONS. To determine whether or not this classification is consistent with results obtained from actual bits drilling these same formations under field conditions, the performance of seven different types of bits used to actually drill several of the tested formations was examined. These bits will be designated as Bit "A", Bit "B", Bit "C", et cetera. Since the DRILLABILITY CLASSIFICATION NUMBER is the time interval required to drill a certain depth, it is equal to the inverse of the rate of penetration if the units are consistent. In any case, the DRILLABILITY CLASSIFICATION NUMBER is inversely proportional to the corresponding rate of penetration of the test bit. Therefore, if the rates of penetration of the actual bits drilling the tested formations under field conditions fall in the same order as the corresponding rates of penetration of the test bit, the DRILLABILITY CLASSIFICATION ESTABLISHED WILL BE CONSISTENT WITH ACTUAL FIELD DRILLING PRACTICES. A COMPARISON OF THE RATES OF PENETRATION OF THE ACTUAL BITS WITH THE RATES OF PENETRATION OF THE TEST BIT IS SHOWN IN TABLE II.
### TABLE II

Comparison of the rates of penetration of actual bits with the rates of penetration of the test bit.

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>DCN&lt;sup&gt;e&lt;/sup&gt;</th>
<th>RATE OF PENETRATION OF TEST BIT (FT/HR)</th>
<th>RATE OF PENETRATION OF ACTUAL BITS (FT/HR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BIT&quot;A&quot;</td>
<td>BIT&quot;B&quot;</td>
</tr>
<tr>
<td>SANDSTONE, Wilcox</td>
<td>1.9</td>
<td>9.88</td>
<td></td>
</tr>
<tr>
<td>LIME, Canyon Reef</td>
<td>2.0</td>
<td>9.38</td>
<td>13.5</td>
</tr>
<tr>
<td>ANHYDRITE</td>
<td>3.4</td>
<td>5.52</td>
<td>7.0</td>
</tr>
<tr>
<td>LIME, Mississippi</td>
<td>3.9</td>
<td>4.82</td>
<td>4.7</td>
</tr>
<tr>
<td>HARD MARINE SHALE, Hosston</td>
<td>4.3</td>
<td>4.37</td>
<td>4.1</td>
</tr>
<tr>
<td>CRYSTALLINE LIME</td>
<td>11.6</td>
<td>1.62</td>
<td>3.6</td>
</tr>
<tr>
<td>CARBONIFEROUS SHALE</td>
<td>15.0</td>
<td>1.25</td>
<td>3.5</td>
</tr>
<tr>
<td>HARD SANDSTONE, First Bromide</td>
<td>19.6</td>
<td>0.957</td>
<td>2.6</td>
</tr>
<tr>
<td>SANDY LIMESTONE, Smackover</td>
<td>26.0</td>
<td>0.722</td>
<td>2.5</td>
</tr>
<tr>
<td>CHERT</td>
<td>45.8</td>
<td>0.408</td>
<td>2.0</td>
</tr>
<tr>
<td>PINK GRANITE</td>
<td>74.1</td>
<td>0.253</td>
<td>1.5</td>
</tr>
<tr>
<td>QUARTZIFEROUS SANDSTONE, Hosston</td>
<td>555.7</td>
<td>0.034</td>
<td>0.9</td>
</tr>
</tbody>
</table>

<sup>e</sup> Drillability Classification Number
The results obtained, as shown in Table II, indicate that the drillability classification established is consistent with actual drilling practices. With the formations arranged in the order of their drillability, the rates of penetration of the actual bits fall in the same order as the rates of penetration of the test bit. This does not mean that there is a direct relationship between the rate of penetration of an actual bit and the rate of penetration of the test bit. It merely shows further that the performance of actual bits normally used to drill the tested formations is analogous to the performance of the test bit. On the basis of these tests, any rolling-cutter type of bit should drill all formations for which a Drillability Classification Number has been established in the same succession as the test bit, if chipping action occurs.

To classify different types of bits with respect to formations, an expanded table similar to Table II could be employed. After compiling rate of penetration data for many types of bits over a long period of time, one type of bit would be found to drill formations which have a certain Drillability Classification Number Range more efficiently than any of the other types. This range would be the sphere of application for that particular type of bit. If a bit manufacturer had more than one type of bit which drilled the same range equally efficiently, then all but one of the types should be eliminated, effecting a saving for the manufacturer. In a similar manner, a manufacturer could obtain a better comparison of his bits with competitors' bits.

As an example of the concepts presented above, consider Table II. The Drillability Classification Number Range of 1.9 to 3.4 would be
most efficiently drilled by Bit "E", the range of 3.9 to 15.0 by Bit "C", the range of 19.6 to 26.0 by Bit "F", and the range of 45.8 to 555.7 by Bit "C". It is of interest to note that Bit "C" drills two ranges most efficiently. The only explanation that can be given for this is that certain features of the design of the bit in combination with certain formation characteristics must produce this dual classification. This is an example of the type of information bit manufacturers can analyze to improve bit designs.

As another example, consider Bits "A" and "B". Bit "B" has a slight advantage over Bit "A" in most instances. Although Bit "A" and Bit "B" are competitive bits, neither should be used because other types of bits drill the entire range more efficiently than either of them; therefore, on the basis of these tests, Bit "A" and Bit "B" should be eliminated. Also, Bits "D" and "G" should be eliminated for the same reason.

A reciprocal use of the table would be to determine which type of bit to use for a formation as yet unclassified. Drillability tests could be made on a core sample of the formation and a Drillability Classification Number determined. On the basis of the Drillability Classification Number alone, a bit could be selected which drills that formation most efficiently. This type of information would be particularly valuable to drillers drilling oil wells in unknown fields, "wildcat drilling."

Now, the question will be raised concerning whether or not the rate of penetration data for actual bits presented in Table II represent the optimum rates for these bits. Reliable data of this nature are
VERY DIFFICULT TO OBTAIN. THE DATA PRESENTED IN TABLE II WERE COMPLIED OVER A PERIOD OF APPROXIMATELY ONE YEAR. EVERY ENTRY REPRESENTS THE AVERAGE RATE OF PENETRATION OF AT LEAST TWO BITS DRILLING IN THE PARTICULAR FORMATION INDICATED. THE SIZE (DIAMETER) OF THESE BITS VARIED BETWEEN 7-7/8 AND 9 INCHES; THE BIT WEIGHT VARIED BETWEEN 30,000 AND 35,000 POUNDS; THE ROTATIONAL SPEED VARIED BETWEEN 50 AND 60 REVOLUTIONS PER MINUTE; THE MUD WEIGHT VARIED BETWEEN 9.5 AND 12.5 POUNDS PER GALLON, AND THE MUD PRESSURE VARIED BETWEEN 800 AND 1100 POUNDS PER SQUARE INCH. ALL OF THE VALUES JUST MENTIONED ARE IN ACCORDANCE WITH ACCEPTED DRILLING PRACTICES WHICH TEND TO PRODUCE THE MOST ECONOMICAL RATES OF PENETRATION RATHER THAN THE MAXIMUM RATES. AS PREVIOUSLY DISCUSSED ON PAGE 8, THE MAXIMUM RATE OF PENETRATION OF A BIT IS NOT THE MOST ECONOMICAL RATE.
DISCUSSION OF GEOLOGICAL FORMATION HARDNESS

An attempt was made to determine the relationship between the hardness and the drillability of formations. Several specimens of different formations were mounted in bakelite and polished. On each specimen micro-hardness tests were made, as shown in Figure 10, using a Knoop indenter. The Knoop hardness of each specimen was determined by averaging ten readings. These hardness values were compared with the Drillability Classification Numbers of the formations, as shown in Table III.

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>DRILLABILITY CLASSIFICATION NUMBER</th>
<th>KNOOP HARDNESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>SANDSTONE, Wilcox</td>
<td>1.9</td>
<td>813</td>
</tr>
<tr>
<td>LIME, Canyon Reef</td>
<td>2.0</td>
<td>630</td>
</tr>
<tr>
<td>ANHYDRITE</td>
<td>3.4</td>
<td>127</td>
</tr>
<tr>
<td>HARD MARINE SHALE, HOSSTON</td>
<td>4.3</td>
<td>176</td>
</tr>
<tr>
<td>SANDSTONE</td>
<td>37.3</td>
<td>988</td>
</tr>
<tr>
<td>CHERT</td>
<td>45.8</td>
<td>745</td>
</tr>
<tr>
<td>QUARTZITIC SANDSTONE, HOSSTON</td>
<td>555.7</td>
<td>1118</td>
</tr>
</tbody>
</table>
On the basis of these tests, no relationship exists between the hardness and drillability of the tested formations. Very hard crystals are present in nearly all formations. These crystals are in many instances harder than steel quenched and tempered to a hardness of 60 on the Rockwell "C" scale. (A hardness of 60 on the Rockwell "C" scale corresponds roughly to a Knoop hardness of 700.) The drillability of formations seems to be more related to the manner by which the hard crystals are bound together than to the hardness. No attempt has been made at this time to investigate the manner by which the hard crystals are bound together. Perhaps some other investigator will conduct such a study.
SUMMARY AND CONCLUSIONS

Within the scope of this thesis, based on tests performed with a small rolling-cutter type of bit, the following has been accomplished:

1. Fifteen representative hard formations have been classified according to the efficiency with which they can be drilled. This classification is called a drillability classification of geological formations. Many more formations could be classified in the same manner.

2. This drillability classification has been shown to be consistent with actual drilling practices if chipping action occurs.

3. A method of classifying different types of bits with respect to the drillability classification has been illustrated. By classifying different types in this manner, a sphere of application for each can be determined. This method of measuring bit performance would reveal bits which have overlapping or coincident spheres of application, and it would provide a means of removing much of the guesswork associated with the selection of a bit for any particular formation.

4. No relationship between the hardness and the drillability of formations could be established. Extremely hard crystals were found in most formations—crystals which are in most instances harder than steel. The drillability seems to be more related to the manner by which the hard crystals are bound together than to the hardness.

In conclusion, the author believes that the results obtained from this investigation are sufficient justification for further study along these lines. The ultimate objective of any further study would be to
Actually classify all types of bits with respect to a drillability classification, as illustrated herein. More formations need to be classified to fill in the gaps in Table 11 and to expand the table to cover a wider range. In particular, a drillability classification needs to be established for formations relatively easier to drill than the ones considered in this thesis. To do this, the method of holding the formation samples will have to be different than the method used in this investigation. One possibility would be to mount the core sample in a plastic which sets at room temperature and atmospheric pressure. It could then be held in the chuck of the lathe. To drill in the less consolidated samples, the bit thrust would have to be less than the thrust used in this study. This suggests that several different classifications should be established, each based on a different bit thrust. These classifications would be analogous to the Rockwell "A", "B", and "C" scales of hardness. They would overlap, but each would cover a different drillability range. With these drillability classifications, all rolling-cutter types of bits could eventually be classified, providing a definite criterion by which a bit could be selected for any particular formation.
ACKNOWLEDGEMENTS

The author takes pleasure in acknowledging his indebtedness to the management of the Reed Roller Bit Company for the cooperation which has made possible this investigation. All the research performed herein was conducted at the company in conjunction with a company research project performed by the author.

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BIBLIOGRAPHY


FIGURE I—DRILLABILITY TEST BIT.
Figure 2—Diamond Core Bit.

Figure 3—Deflection Scale.
FIGURE 4—RELATIONSHIP BETWEEN LOAD APPLIED AND INDICATOR READING FOR DEFLECTION SCALE.
FIGURE 5—THE RELATIONSHIP BETWEEN CABLE LOAD AND BIT THRUST FOR DRILLABILITY TEST APPARATUS.
FIGURE 6—DRILLABILITY TEST APPARATUS.
FIGURE 7—RELATIONSHIP BETWEEN BIT THRUST AND RATE OF PENETRATION FOR DRILLABILITY TEST BIT IN WEST TEXAS CHERT.
DIAMOND CORE BIT IN OPERATION.
"A"

DRILLABILITY TEST BIT IN OPERATION.
"B"

FIGURE 8.

9/12/50
ALH
WORK AREA OF DRILLABILITY TEST APPARATUS.
"A"

FORMATION SAMPLE AFTER BEING DRILLED.
"B"

FIGURE 9
FIGURE 10—PHOTOMICROGRAPH OF A POLISHED SPECIMEN OF HARD SANDSTONE FROM THE 1st BROMIDES OF THE LINDSAY, OKLAHOMA, FIELD SHOWING INDENTATIONS MADE BY A KNOOP INDENTER.