Dec. 17, 1968 R. J. GOODWIN ETAL 3,416,614

HYDRAULIC JET DRILLING METHOD USING FERROUS ABRASIVES

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2 Sheets-Sheet 1

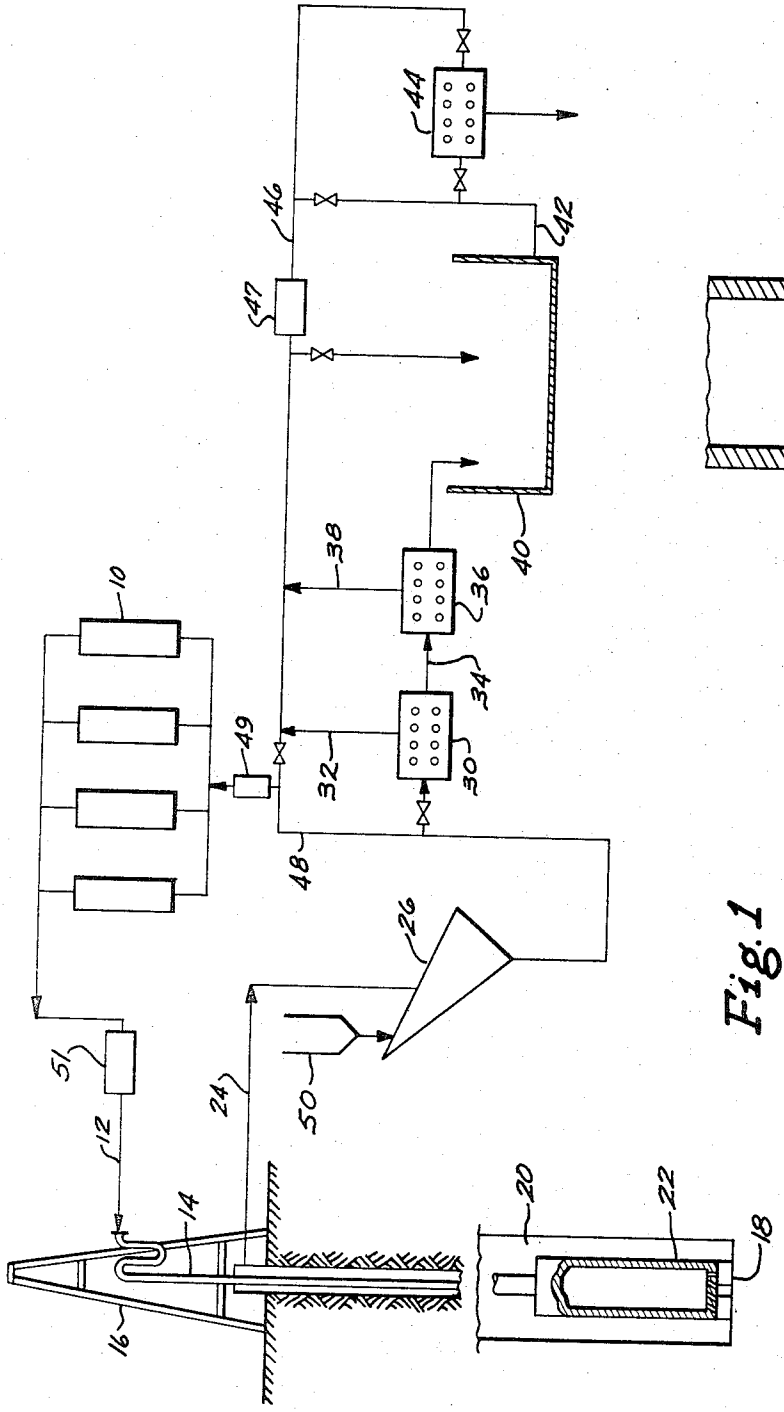


Fig. 1

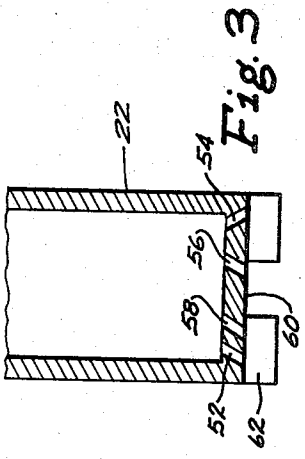


Fig. 3

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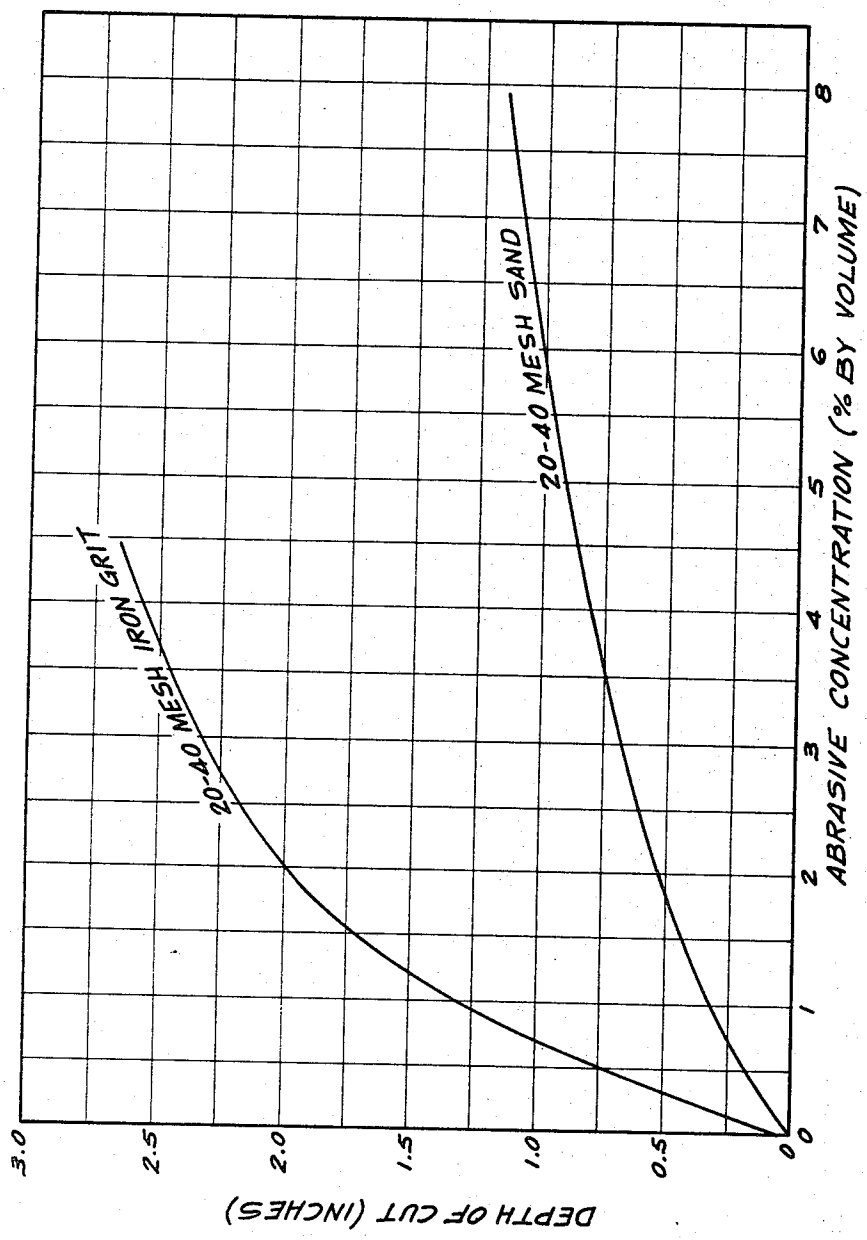


Fig. 2

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HYDRAULIC JET DRILLING METHOD USING FERROUS ABRASIVES

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ABSTRACT OF THE DISCLOSURE

A method of drilling hard rock formations in which particles of ferrous abrasives having a size in the range of 7 to 80 mesh are suspended in a drilling liquid. The drilling liquid is pumped down rotating drill pipe in a well and discharged at a velocity of at least 500 feet per second through tungsten carbide nozzles in a drill bit at the lower end of the drill pipe to cut the formation being drilled. The ferrous abrasives give increased drilling rates with reduced wear of the nozzles in the drill bit.

This application is a continuation-in-part of copending application Ser. No. 311,088, entitled Method and Apparatus, fi'ed Sept. 24, 1963 by Robert J. Goodwin, Ernest A. Mori, Joseph L. Pekarek, Paul W. Schaub and Robert E. Zinkham, now abandoned.

This invention relates to the drilling of wells, and more particularly to an improved drilling process in which a stream of drilling liquid containing suspended ferrous abrasive is discharged at extremely high velocities against the bottom of a borehole to drill through hard formations.

Improvements in conventional rotary drilling processes have greatly increased rates of drilling in soft formations and formations of medium hardness. To a large extent, the improvements have resulted from more powerful equipment which allows the application of greater bit weights to cone or drag-type bits. One type of bit that is used widely to drill soft formations is referred to as the "jet bit." It differs from the usual bit principally in directing the drilling mud against the bottom of the hole to clean the bottom of the hole rather than over the surface of the cutters to keep the cutters clean. The purpose of jet bits is to improve the removal of cuttings broken from the formation by the mechanical cutting elements of bits rather than to cut grooves in the formation being drilled; however, some penetration of soft formations by the stream of drilling mud may be responsible for some of the increase in drilling rate. Quick removal of the cuttings from the bottom of the hole reduces shielding of the bottom of the ho'e from the bit by the cuttings and reduces regrinding of cuttings. The conventional jet bits have been ineffective in increasing substantially the rate of drilling in hard formations.

Recently, a novel hydraulic jet drilling process which is effective in increasing the rate of drilling of hard formations has been developed. In the hydraulic jet drilling process, an abrasive-laden liquid is discharged at extreme'y high velocities against the bottom of the hole to cut the formation being drilled and remove cuttings from the hole. Substantially all of the penetration of the rock being drilled in the hydraulic jet drilling process is accomplished by the abrasive-laden stream, and mechanical removal of rock from the bottom of the hole by engagement with a bit is restricted to removal of ridges which may extend upward between grooves cut by the high-velocity stream. In the hydraulic jet drilling process, the weight applied to the nozzle head, referred to for convenience as the "bit," is approximately one-fourth, or less, of the weight applied in comparable conventional drilling methods. Hydrau'ic jet drilling in hard formations is substantially faster than drilling with conventional rock bits but is still relatively slow compared to drilling in soft formations, and further increases in hydraulic jet drilling rates are desirable.

The high velocity at which the abrasive-laden stream passes through nozzles in the bit causes rapid erosion of the nozzle with a resultant increase in the diameter of the orifice in the nozzle. Because the rate of drilling is highly dependent upon the velocity at which the abrasive-laden stream strikes the bottom of the borehole, the reduced velocity resulting from enlargement of the nozzle orifice reduces the drilling rate and makes it necessary to replace the bit. In deep wells, a substantial part of the rig time can be used in making the round trips necessary to replace the bit. For this reason, it is important to reduce the rate of erosion of the nozzles.

When the high-velocity stream of abrasive-laden liquid strikes the formation being drilled, the abrasive, as well as the formation, is subjected to severe stresses. When sand is used as the abrasive in the drilling, approximately one-half of the sand is broken up in a single pass through the bit into fine particles unsuited for further use. The large amounts of abrasive consumed cause the abrasive to be an important part of the cost of the hydraulic jet drilling process. It is desirable to use an abrasive that breaks up only to a negligible extent on striking the bottom of the borehole and, hence, can be reused to reduce the abrasive requirements.

This invention resides in a hydraulic jet drilling method for the drilling of boreholes in hard formations in which a ferrous abrasive is suspended in a liquid to form a drilling liquid that is discharged through nozzles spaced at different distances from the center of rotation of a drill bit to cut a plurality of concentric grooves over the major portion of the bottom of the borehole. The drilling liquid is discharged from the nozzles at a distance of ¼ inch to 1¼ inches above the highest portion of the bottom of the borehole and at a velocity of at least 500 feet per second. The liquid in which the ferrous abrasive is suspended to form the drilling liquid has an apparent viscosity on the Fann viscometer of at least 50 centipoises at 600 r.pm. and a minimum zero gel strength, also measured on the Fann machine, of 50 pounds per 100 square feet both before and after passing through the nozzles.

FIGURE 1 of the drawings is a diagrammatic flow sheet of this invention showing a system for handling the drilling liquid used in the drilling process of this invention with the lower portion of the borehole enlarged.

FIGURE 2 is a chart comparing the rate of penetration of a hard rock by a drilling liquid containing a ferrous abrasive with the rate of penetration by a drilling liquid containing sand in hydraulic jet drilling processes.

FIGURE 3 is an enlarged diagrammatic view of the drill bit shown in FIGURE 1.

In the hydraulic jet drilling process of this invention, particles of ferrous abrasive are suspended in a liquid to form a drilling liquid which is pumped down drill pipe having a drill bit mounted on its lower end. The drill bit has a plurality of nozzles opening through its lower end for discharging the drilling liquid at a high velocity against the bottom of the borehole to penetrate the bottom of the borehole. The nozzles are positioned at different distances from the center of rotation to cut a plurality of concentric grooves in the bottom of the borehole as the bit is rotated. The nozzles may be positioned to cut overlapping grooves, but it is preferred that the nozzles be positioned to cut a central hole in the bottom of the borehole and a plurality

of concentric grooves spaced from one another to leave intervening ridges which can easily be mechanically broken.

The drilling liquid is pumped down the drill pipe at a rate and pressure to cause a pressure drop through the orifices of at least about 4,000 p.s.i. to impart a velocity of at least 500 feet per second, and preferably more than 600 feet per second, to the drilling liquid discharged from the nozzles. Stand-off bars on the bottom of the drill bit body extend downwardly below the nozzle outlets and maintain the desired spacing of ¼ inch to 1¼ inches from the nozzle outlets to the ridges on the bottom of the borehole.

After the discharge from the nozzles, the drilling liquid and entrained cuttings circulate upwardly through the borehole around the drill pipe and are discharged at the surface for treatment to remove cuttings and put the drilling liquid in condition for recirculating in the drilling system.

The ferrous abrasive used in the hydraulic jet drilling process of this invention may be either cast iron particles or steel particles readily available as commercial products used in the cleaning and treating of metal surfaces. Ferrous abrasives can be manufactured by blowing a high-velocity stream of air or steam against molten cast iron or steel to separate globules of the metal. The globules are blown into water where they are chilled. The solidified particles are heat treated and graded by size. Grit is prepared by crushing shot and then heat treating the granular particles and grading them according to size. Either angular granular particles, referred to as "grit," or rounded particles, referred to as "shot" can be used, but the shot are preferred because of faster cutting rates obtained with them.

The ferrous particles used in this invention have a size larger than 80 mesh in the U.S. Sieve series. The drilling rate is faster with the particles of larger size, and it is desirable to use the largest particles that will pass through the nozzles in the drill bit without plugging the nozzles and that can be handled by the high-pressure pumps. In nozzles having an orifice ⅛ inch in diameter, ferrous abrasive particles in the range of 7 to 80 mesh can be used. A preferred range of abrasive particle sizes is 16 to 50 mesh. Larger particles can be used with larger orifices, but it is not possible to handle particles much larger than 7 mesh with the pumps presently available. An arrangement that has been used successfully with ⅛ inch nozzles is to screen all cuttings and abrasive particles larger than 10 mesh before delivering them to the high-pressure pumps. Ferrous abrasive particles in the 50–80 mesh range cause drilling rates approximately equal to sand particles in the preferred range of particle sizes for sand and are retained in the drilling liquid to reduce the amount of abrasives required.

The ferrous abrasive particles are suspended in a drilling liquid in a concentration of ½ to 6 percent, preferably 1 to 4 percent by volume. Higher concentrations increase the amount of abrasive in the system and the total break-up of the abrasive without a corresponding increase in drilling rate. Lower concentrations of abrasive markedly reduce the drilling rate.

Drilling liquids suitable for use in hydraulic jet drilling processes using sand as an abrasive are not suitable for use in this invention. The drilling liquids used to suspend the ferrous abrasive must have a relatively high gel strength and viscosity to remove the abrasive from the hole during the drilling operation and to prevent settling of the abrasive in the borehole when it is necessary to stop the circulation of the drilling liquid. The drilling liquid should have a minimum viscosity of at least 50 centipoises as determined on the Fann viscometer at 600 r.p.m. and an initial or zero time gel strength of at least 50 pounds per 100 square feet. The drilling liquid should have a pH of at least 8.5 and preferably in the range of 8.5–10. Viscosities and gel strengths above the minimum specified are necessary to prevent excessive settling of the ferrous abrasive from the drilling liquid on those occasions when circulation of the drilling liquid in the hole is interrupted. We have found that many of the compositions ordinarily employed to increase the viscosity of liquids suffer a serious reduction in viscosity upon passing at high velocities through nozzles such as those in the drill bit. It is not only essential that the drilling liquid have the minimum specified viscosity in gel strength as it is pumped down the drill pipe, but it is also essential that the viscosity and gel strength of the drilling liquid be above the minimums specified after passing through the nozzles at a rate resulting in a pressure drop through the nozzles of at least 4,000 p.s.i.

A suitable drilling liquid is an invert emulsion of water and diesel oil containing 30 to 60 percent oil, with the oil in the continuous phase. A preferred drilling liquid is an invert emulsion containing 40 to 50 percent diesel oil. The emulsion can be stabilized by, for example, a sulfurized potassium soap of tall oil containing 5 percent sulfur. Other emulsifiers, such as polyhydric alcohol fatty acid esters, sulfated sperm oil soaps, and polyvalent metal soaps of rosin acids can be used. The pH of the drilling liquid is adjusted to the range of 9 to 10 by the addition of alkaline material such as caustic soda. Another suitable drilling liquid is an aqueous dispersion of bentonite containing 2 percent bentonite and 1 to 2 percent Flosal, a fibrous asbestos material. The Flosal drilling mud should have a pH of 8.5 to 9.5 to reduce corrosion of the drilling equipment and abrasive. Hydraulic jet drilling with a ferrous-abrasive-laden drilling liquid is not limited to the use of any particular drilling liquid as long as the drilling liquid has adequate gel strength and viscosity to give satisfactory suspension of the abrasive particles.

For purposes of illustration, a hydraulic jet drilling process will be described in which 20 to 40 mesh particles of Indogrit, a cast iron granular material, manufactured by Industeel Company of Pittsburgh, Pa., is suspended in a concentration, by volume, of 2 percent in an invert emulsion drilling liquid containing 50 percent diesel oil. The drilling liquid is delivered by high-pressure pumps **10** through a line **12** into the drill string **14** of a drilling rig **16** suitably equipped to rotate the drill string in the borehole. The drilling liquid is pumped at a high rate downwardly through the drill pipe **14** and discharged against the bottom **18** of the borehole **20** through nozzles ⅛ inch in diameter in a bit **22** at the lower end of the drill pipe. Drill pipe **14** is rotated at a rate of at least 5 r.p.m. during the drilling.

The drilling liquid and entrained cuttings pass upwardly through the borehole and are discharged therefrom through line **24** and delivered to a shale shaker **26** in which oversize cuttings larger than 10 mesh are removed from the drilling liquid. Ferrous-grit-laden drilling liquid is delivered through line **28** to a bank of cyclone separators **30** in which abrasive particles are separated from the liquid and delivered as an underflow through line **32**. Overflow from separators **30** is delivered through line **34** to a second bank **36** of separators in which further clean-up of ferrous-grit particles from the drilling liquid is accomplished, and the ferrous-grit particles separated in separators **36** are discharged as underflow through line **38**.

Overflow from separators **36**, which contains less than 0.2 percent particles larger than 200 mesh, is delivered into a storage tank **40**. Ferrous-grit-free drilling liquid is withdrawn from tank **40** through line **42** and passed through another bank of cyclone separators **44** for removal of fine solid particles of 200 mesh size and smaller to reduce the concentration of larger than 200 mesh particles to a trace and control the density of the drilling liquid. Clean drilling liquid from the separators **44** is delivered through line **46** to the high-pressure pumps **10**. Abrasive from lines **32** and **38** is mixed with the clean drilling liquid for recirculation in the well. Because of the low rate of break-up of ferrous abrasives, removal of fines from all of the liquid

circulated in the borehole is not required and drilling liquid may be delivered from the shale shaker directly to pumps **10** through a suitably valved bypass line **48**. Heat exchangers **47** and **49** are provided for control of the temperature of the drilling liquid. A temperature of 140°–170° F. is preferred when using the invert emulsion drilling mud. Tests on nozzles in the drilling bit have indicated that drilling liquid temperatures above 140° F. increase nozzle life. Valves are provided as required to allow delivery of liquid from tank **40** directly or indirectly through separators **44**, to pumps **10**, or to circulate the drilling liquid. An in-line screen **51** in line **12** removes large solid particles which might plug nozzles in the drill bit. Make-up abrasive is added to the system at shale shaker **26** from a storage hopper **50**.

For effective drilling by the hydraulic jet drilling method, the drilling liquid must be discharged at a velocity of at least 500 feet per second, and preferably at least 600 feet per second, from nozzles having an outlet ½ inch to 1½ inches from the bottom of the borehole. In a typical hydraulic jet drilling operation, the four pumps **10** supply a total of about 2,000 to 2,400 horsepower and deliver 450 to 600 gallons per minute of the drilling liquid at a pressure of 5,000 p.s.i. to the drill pipe **14** for delivery to a drill bit having a plurality of nozzles. A typical drill bit for such an operation will have 10 to 20 nozzles ⅛ inch in diameter.

Referring to FIGURE 3, a drill bit **22** is shown having outer nozzles **52** and **54** positioned and slanting to discharge a stream against the bottom of the borehole and a location to cut a hole having a large enough gauge to permit free movement of the drill bit **22** downwardly. Drill bit **22** is shown with an inner nozzle **56** slanting toward the center of rotation of the drill bit to cut a central hole in the bottom of the borehole. Intermediate nozzles **58** are provided between the inner nozzle **56** and the outer nozzles to cut grooves in the bottom of the borehole between those cut by the inner nozzle and the outer nozzle. The number of intermediate nozzles **58** and their location will depend upon the size of the borehole being cut. A sufficient number of nozzles at different radial distances from the center of rotation of the drill bit should be provided to cause penetration of the formation being drilled to be accomplished by the high velocity abrasive stream and to cause the major portion of the rock removal to be the result of cutting by the abrasive stream. The nozzles may be positioned so that there is some overlapping of the paths traveled by the drilling liquid discharged from the nozzles. It is preferred, however, that the nozzles be spaced to cut grooves in the bottom of the borehole separated by thin, easily broken ridges that are exposed on their inner and outer faces whereby they can be easily broken by bit weights not exceeding about 700 pounds per inch diameter.

The nozzles in the bottom of the bit for the discharge of drilling liquid are provided with nozzle inserts, not shown in the drawings, of tungsten carbide or other very hard abrasive-resistant material to increase the life of the bits. It is inherent in the hydraulic jet drilling process that the nozzles are subjected to severe erosive conditions. The outlet of the nozzles should be positioned approximately at the lower face **60** of the drill bit. Stand-off bars **62** extend downwardly from the lower surface of the drill bit and engage the ridges on the bottom of the borehole to support the bit with the orifice outlet at the desired distance of ¼ inch to 1¼ inches above the ridges in the bottom of the borehole. Stand-off bars **62** are also subjected to severe abrasion and are constructed of a hard material such as tungsten carbide. By cutting a central hole and a plurality of closely spaced concentric grooves, the intervening ridges are thin and unsupported which allow them to be readily broken from the bottom of the hole by the stand-off bars.

The ferrous grit particles are effective in increasing the drilling rate over that which is obtained with other abrasive particles such as sand. A series of tests was made in which the abrasive-laden drilling liquid was discharged from a single nozzle onto a block of hard black granite rotated in a horizontal plane about an axis 1½ inches from the bit axis at a rate of about 30 r.p.m. The outlet of the nozzle was maintained ½ inch from the original rock surface during the tests. The tests were made at a nozzle inlet pressure of 5,000 p.s.i. and a drilling liquid velocity of approximately 776 feet per second. Each test was continued for a period of 20 seconds after which the depth of the cut was measured to give an indication of the drilling rate. Test runs were made on drilling liquids containing different concentrations of 20–40 mesh cast iron and with sand of the same size. The results are presented in FIGURE 2. The data presented in FIGURE 2 show that ferrous abrasives cause much higher drilling rates than sand in hydraulic drilling operations.

During the cutting test described above, the drilling liquid samples were caught, diluted, screened, dried, weighed, sieved, and reweighed. These data were then reduced to an average percentage of particles larger than 40 mesh broken to smaller than 40 mesh. The results of the particle break-up determinations are presented in Table I.

TABLE I

Material and mesh range:	Percent break-up
20–40 mesh sand	50–60
20–40 mesh steel spheres	1–4
20–40 mesh ferrous grit	1–4

Because of the extremely high velocities of the drilling liquid passing through the nozzles, erosion of the nozzles is an important factor in determining the feasibility of hydraulic jet drilling. A series of tests was run in which 20 to 40 mesh sand particles were pumped through a nozzle having a ⅜ inch diameter inlet tapering down to a ⅛ inch diameter orifice over a distance of 2½ inches and a straight section ½ inch long and ⅛ inch in diameter extending from the orifice to the nozzle outlet. In the test, suspensions of 20 to 40 mesh cast iron and of 20 to 40 mesh sand were caused to flow through the nozzle at rates giving a pressure drop across the nozzle of 5,000 p.s.i. or more. The nozzles were constructed of two types of tungsten carbide. The results of the tests are presented in Table II.

TABLE II.—NOZZLE WEAR TESTS

[Test duration, 6 hours]

Nozzle designation	Abrasive	Conc. percent by Vol.	Pressure (p.s.i.) across nozzle	Increase in nozzle diameter (inch)
Tungsten carbide I	Cast iron	1.5	7,000	0.0018
Do	Sand (20–40)	6	5,000	0.004–0.005
Tungsten Carbide II	Cast iron	1.5	7,000	0.0036
Do	Sand (20–40)	6	5,000	0.013

The results presented in Table II show that nozzle wear is much lower when a ferrous abrasive is suspended in the drilling liquid than when the abrasive is sand in spite of the fact that the ferrous abrasive causes a much higher drilling rate. Because the drilling rate is a measure of the ability of the drilling liquid to cut a hard surface, it is surprising that the nozzle erosion is less when iron grit is suspended in the drilling liquid than when sand is suspended in the drilling liquid.

Both cast iron and steel shot and grit are highly advan-

tageous in hydraulic jet drilling operations in making possible high drilling rates through very hard rock formations. The high drilling rates can be obtained with a relatively low rate of erosion of the nozzles through which the drilling liquid is discharged against the bottom of the hole. Moreover, the low rate of break-up of the ferrous grit particles allows their repeated use, and thereby greatly reduces the cost of the abrasive required in hydraulic jet drilling.

We claim:

1. A hydraulic jet drilling process for the drilling of boreholes in hard rock formations comprising suspending 7–80 mesh ferrous abrasive particles in a concentration of ½ to 6 percent by volume in a liquid to form a drilling liquid having a minimum viscosity of 50 centipoises at 600 r.p.m. on the Fann viscometer, a zero gel strength of at least 50 pounds per 100 square feet, and a pH of at least 8.5, pumping the drilling liquid down drill pipe in the borehole to a bit mounted on the lower end of the drill pipe, discharging the drilling liquid from downwardly opening nozzles in the bit at a velocity of at least 500 feet per second, rotating the bit whereby the streams of drilling liquid discharged from the nozzles cut a plurality of concentric grooves in the bottom of the borehole, said nozzles being spaced at different radial distances from the center of the bit whereby a central hole and a plurality of concentric grooves are cut in the bottom of the borehole with the outer groove having desired borehole diameter and the grooves are separated by intervening ridges having a maximum thickness of about ½ inch, supporting the drill bit on said intervening ridges with the outlet of the nozzles ¼ inch to 1¼ inches above the ridges, and circulating cuttings upwardly around the drill pipe.

2. A process as set forth in claim 1 in which the pressure drop through the nozzles is at least 4,000 p.s.i.

3. A hydraulic jet drilling process as set forth in claim 1 in which the drilling liquid is an invert emulsion and is passed through heat exchangers before pumping down drill pipe in the borehole to maintain the drilling liquid in the range of 140° to 170° F., and the internal surfaces of the nozzles are tungsten carbide.

4. A hydraulic jet drilling process for the drilling of boreholes in hard rock formations comprising suspending 7–80 mesh ferrous abrasive particles in a concentration of ½ to 6 percent by volume in a liquid to form a drilling liquid, delivering the drilling liquid down drill pipe in a well to a drll bit, rotating the drill bit about a vertical axis, discharging the drilling liquid at a velocity of at least 500 feet per second downwardly and outwardly from outwardly slanting first nozzles in the bit near the perimeter thereof to cut a borehole of the desired gauge, discharging drilling liquid downwardly and inwardly at a velocity of at least 500 feet per second from an inwardly slanting nozzle positioned near the center of the bit to cut a central hole, discharging drilling liquid downwardly at a velocity of at least 500 feet per second from intervening nozzles between the first nozzles and the inwardly slanting nozzle to cut grooves in the bottom of the borehole with intervening ridges having a maximum thickness of about ½ inch, supporting the bit on the bottom of the borehole with the nozzle outlets ½ inch to 1¼ inches above the bottom of the borehole, circulating the drilling liquid and entrained cuttings upward through the borehole around the drill pipe, and discharging the drilling liquid and entrained cuttings from the well at the ground surface.

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