Dec. 17, 1968 H. I. HENDERSON 3,416,613

COMBINED ROTARY AND PERCUSSION DRILL UTILIZING LIQUID DRILLING FLUID

Filed April 14, 1966 2 Sheets-Sheet 1

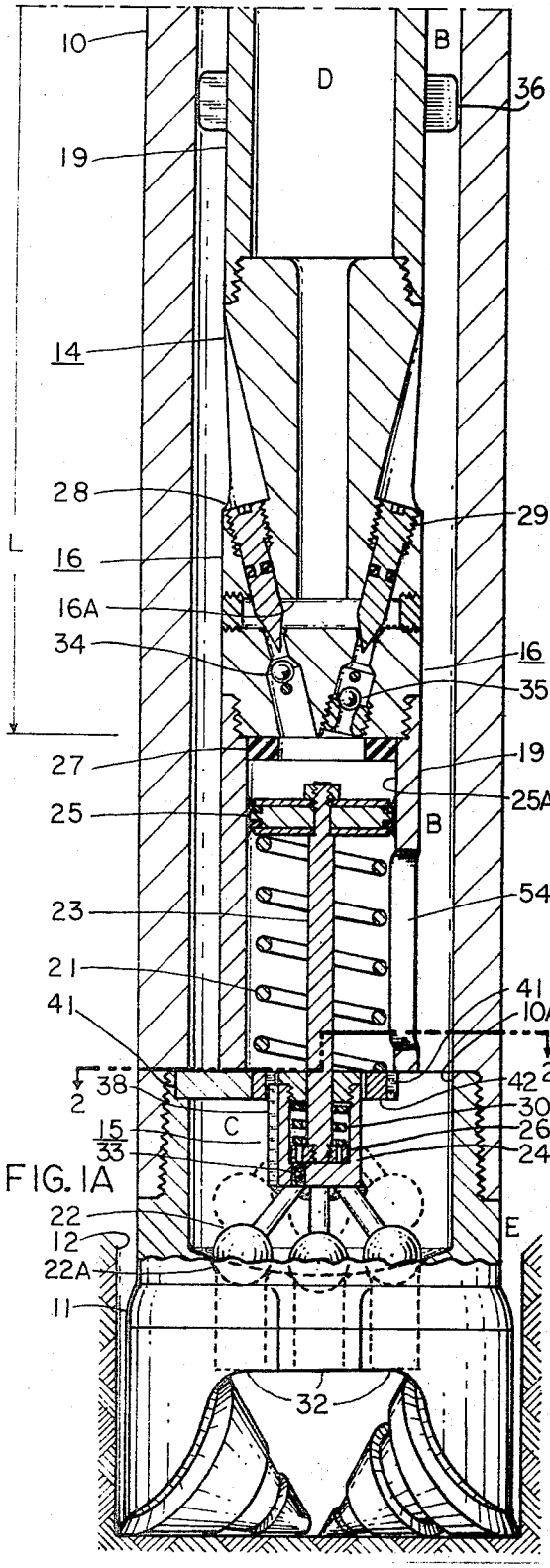


FIG. 1A

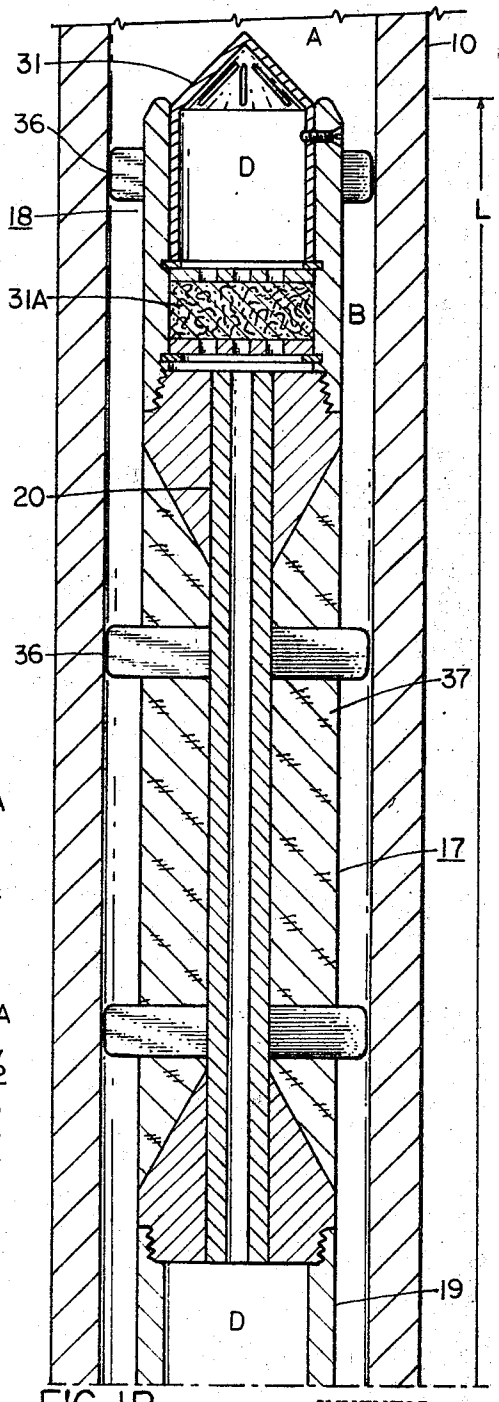


FIG. 1B

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COMBINED ROTARY AND PERCUSSION DRILL UTILIZING LIQUID DRILLING FLUID

Filed April 14, 1966 2 Sheets-Sheet 2

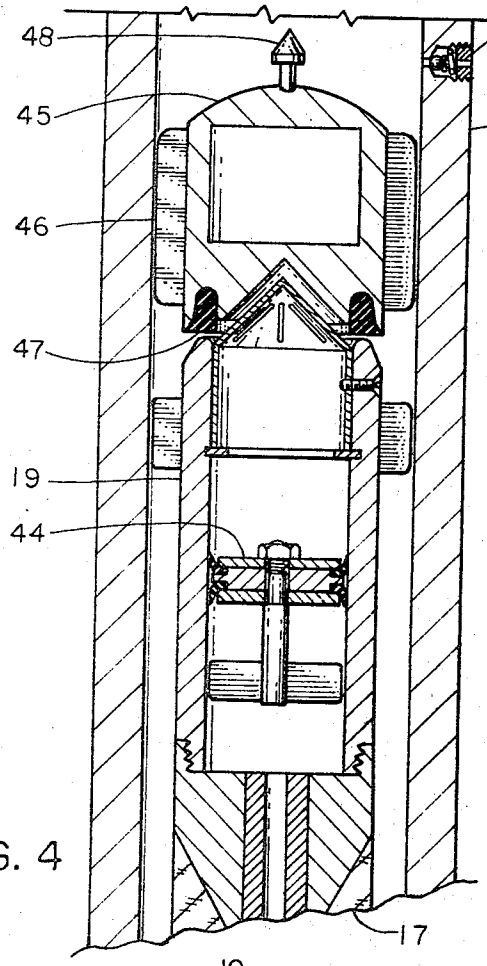


FIG. 4

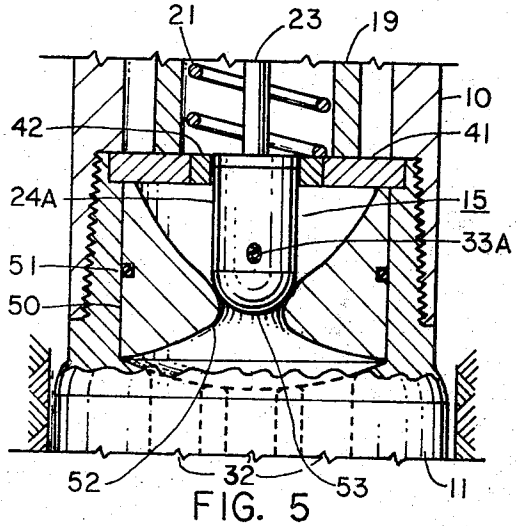


FIG. 5

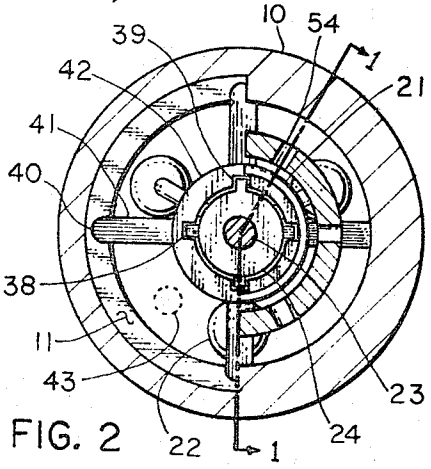


FIG. 2

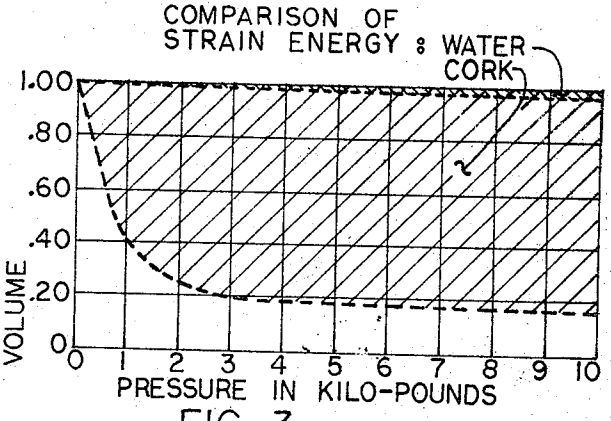


FIG. 3

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3,416,613

COMBINED ROTARY AND PERCUSSION DRILL UTILIZING LIQUID DRILLING FLUID

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Filed Apr. 14, 1966, Ser. No. 542,571
11 Claims. (Cl. 173—57)

ABSTRACT OF THE DISCLOSURE

A combined rotary and percussion drill having an elongated, open top tube within the drill pipe or drill collar. The tube is closed at the lower end by a pressure-responsive member such as a piston which operates a valve to shut off fluid circulation. The other side of the piston is exposed to fluid flowing through the drill string around the inner tube. When friction losses in the flowing stream reduce its pressure by an amount lower than the near static stream in the inner tube sufficient to overcome a spring, the piston is operated to close the valve and generate a pressure wave against the drill bit.

This invention relates to a combined rotary and percussion drill and, more particularly, to a rotary drilling apparatus adapted for operation while circulating the liquid cooling and scavenging medium, and wherein intermittent pressure waves are generated to superimpose a percussion effect on a conventional rotary type cutting bit.

Others have been successful in the development of percussion drills, even in combination with a rotary drill, as long as gas is used in the circulating medium. Such percussion devices generally take the form of a piston-driven hammer that is operated by valving devices which selectively direct the gas to raise and lower the hammer. Superimposing a percussion effect on a rotary drill will greatly increase the rate of penetration and hence reduce the cost per foot of "making hole", but its limitation to use with gas has greatly restricted its value to the drilling industry. By far the great majority of rotary drilling today involves the use of equipment that circulates liquid as the drilling fluid, and there has long existed a great need for development of a satisfactory percussion tool that will operate successfully in such equipment.

It is, therefore, an object of this invention to provide a rotary drilling device, the cutting action of which is augmented by periodic percussion blows delivered through a liquid medium.

It is a further object of this invention to provide a rotary drilling device with means for delivering repeated pressure waves or water hammer blows to the top of the drilling bit.

It is a further object of this invention to provide a rotary drilling device with means for delivering repeated and automatically controlled fluid hammer blows.

It is a further object of this invention to provide a combined rotary and percussion drilling device wherein the percussion blows are developed from periodic high pressure waves with means for confining such high pressure waves to relatively thick-walled drill collars at the lower end of the drill string.

If the drilling fluid flows at a steady rate through the bit nozzle, a definite and regular flow pattern is established involving reversal of flow direction from downward to upward. The resultant eddy currents tend to accumulate cuttings at the outside of the bore hole bottom, i.e., "the corner of the hole," If such cuttings are permitted to accumulate at the bottom of the hole, they may be compacted by the rolling cutter bits into an indurated mass, greatly to impede drilling progress. Thus, it is of distinct

advantage to provide, together with percussion means for breaking up the mass, means for ejecting high velocity jets intermittently with no continuous or set flow pattern, to minimize the accumulation of cuttings.

It is, therefore, a further object of this invention to provide drilling apparatus which delivers a repeated series of jets and corresponding percussion blows.

In order for a drill bit to cut efficiently through hard rock, it is necessary that it be urged against the rock with a force of substantial magnitude in order to crush it. In deep drilling this force is achieved by weighting the lower portion of the drill string with a series of thick-walled heavy pipe sections, known as drill collars. However, when drilling near the surface, there is frequently insufficient hole depth to accommodate long strings of drill collars and the crushing force must be delivered by other means.

It is, therefore, a further object of this invention to provide means for delivering a crushing force to the drill bit at even very shallow depths.

In carrying out this invention, I provide above the drill bit a fluid pressure-responsive member, such as a piston, that is operated periodically, each time to close a valve and shut off part or all of the flow of liquid being circulated through the drill pipe. The resultant pressure wave or water hammer effect above the drill bit, coupled with the concommitant decrease in pressure below the drill bit, is delivered against the formation in the form of a percussion blow, thus augmenting the rotary drilling action. Preferably, the pressure-responsive member is operated to shut the valve in response to a predetermined pressure differential between the flowing circulating fluid and a relatively stationary column of fluid delivered from the same pressure source. This is accomplished by provision within the drill pipe string of an inner tube closed at the bottom by a pressure-responsive member so that the column of fluid within the tube is nearly static and under pump pressure plus static head. The other side of the pressure response member is exposed to the fluid flowing within the drill string around the inner tube. Since the circulating fluid suffers loss of pressure as a result of friction, a pressure differential builds up between it and the standing column. It is this pressure differential that operates the pressure-responsive member and closes the valve.

Other objects and advantages of this invention will become apparent from the description following, when read in conjunction with the accompanying drawings wherein:

FIGS. 1A and 1B are vertical sectional views of the lower and upper portions, respectively, of drilling apparatus embodying features of this invention;

FIG. 2 is a horizontal sectional view taken along line 2—2 of FIG. 1A;

FIG. 3 is a graph illustrating the strain energy characteristics of water and cork as contemplated in this invention;

FIG. 4 is another embodiment of the upper portion of this drilling device; and

FIG. 5 is a modified valve embodying features of this invention.

Referring now more particularly to FIGS. 1A and 1B, there is shown a drill collar **10** at the lower end of which is threadedly connected a drill bit **11** which may be of any conventional type for penetration of the formation **12** in response to rotation of the drill collar. As is well known in the drilling art, rotation of the bit is produced by operation of surface rotary equipment through a string of drill pipe (not shown). For purposes of illustration, I have shown a typical cone rock bit to which a series of percussion blows is to be delivered from the apparatus to be de-

scribed. Moving upward from the bit **11**, the percussion generating means is made up of four principal sections. Specifically, they are the pulse wave generating section **15**, the pressure differentiating section **16**, the pressure wave suppressor or dampener section **17** (FIG. 1B) and a filtering intake static head section **18**.

Considering first the pulse wave generating section **15**, there is shown a plurality of ball-like valve members **22** in pulse generating chamber C. The valve balls are normally elevated above their seats in open position shown in phantom in FIG. 1A, but they are periodically moved against the seats **22***a*, suddenly to close off flow of circulating fluid out through the bit nozzles **32**. The sudden closing of the valves generates a water hammer, i.e., a high-pressure pulse, above the bit **11** which is delivered through the bit as a percussion blow against the formation **12**. At the same time, the momentum of the fluid projected from the nozzles carries it out from under the bit and up the hole to reduce the pressure of fluid opposing the blow.

The valves **22** are closed in response to the downward stroke of a piston **25** which is slidably carried within a cylinder **25***a* at the lower end of a long tubular housing **19**, the piston being normally urged upward by means of a compression spring **21**. The piston rod **23**, depending from the piston, preferably terminates in an enlarged perforated head **26** which is slidably received in a dashpot cylinder **24**. The cylinder **24** is, in turn, slidably mounted in the drill collar **10** by engagement of a series of radial ribs **38** (FIG. 2) in complementary grooves **39** which are formed in a stationary ring **42**. The ring **42** is mounted on a spider **41**, the legs of which are locked in grooves **40** by the thread shoulder **10***a* of the lowest drill collar section **10**. The engagement of the ribs **38** within the groove ring prevents rotation of the valve ball assembly so that they are maintained in proper orientation over the complementary valve seats **22***a*, and proper operation is thereby assured. Thus, the piston rod **23** and the dampener cylinder **24** move as a unit with the telescopic connection of the perforated head **26** and the cylinder providing a dampening or delaying effect under certain conditions, as will be explained.

The telescopic, extensible and retractable connection is limited only by contraction of a relatively weak spring **30**. As the piston **25** is driven downward, direct engagement of the perforated head **26** with the bottom of the cylinder delivers a positive, mechanical drive to the valve ball **22** to move them toward their seats **22***a*. However, as they near the seats, they restrict flow through the nozzles **32** to create a high velocity, low pressure condition under them, so that the pressure drop across the balls overcomes the springs to drive the ball valves against their seats **22***a* into firm sealing engagement. This creates a high-pressure wave in the chamber C, which moves upward through the drill collar **10** and against the bottom of the piston **25** to drive it upward again. The initial upward movement of the piston **25** is absorbed in compression of the spring **30** to delay valve opening, and it is not until after the spring is fully compressed at approximately three-fourths of the full travel of the piston that a positive drive is achieved to unseat the valve balls. Then, when the piston **25** moves toward its upper position, the spring **30** expands to push the top of the ribbed cylinder **24** upward and carry the valve balls well above their seats. A breather hole **33** is also provided at the bottom of the cylinder, and this may be provided with a filter screen.

If desired, fluid tight resilient sealing may be achieved by making either the valve balls **22** or the valve seats **22***a* of resilient material, with the other being formed of hard material such as metal. A shock absorbing pad **27** may be placed at the upper end of the cylinder **25***a* at the top of the piston travel. In addition, as shown in phantom in FIG. 2, an open bypass nozzle **43** may be provided if it is desired to maintain some flow constantly.

Describing now the means for reciprocating the piston **25** to open and close the drill bit nozzles **32** and generate repeated pressure waves, an inner column or conduit D of length L is supported within the drill collar **10** to extend upward from the top of the cylinder **25***a* in which the piston is slidably carried. The inner conduit D is supported on the spider **41** and is formed by the pipe **19**, with the throttle valve section **16** interposed therein, the tubular core **20** of the pressure wave suppressor section **17** and the intake section **18**. Preferably, radial ribs **36** are secured along the various sections in order to center the column within the drill collar **10**.

As in conventional rotary drilling, drilling mud or water is pumped down the flow passageway A of the drill pipe and drill collar string **10** until it reaches the perforated cap **31** at the upper end of the column D. There the flow is divided, with the majority flowing through the annulus B around the pipe **18**, and the remainder entering the column D. The perforated cap **31** blocks entry of all but the smallest particles of mud and foreign matter and, in addition, a filter unit **31***a* is provided to remove any remaining solids which might otherwise impair valve or piston operation. The filtered fluid flows down the column D to build up a virtually static column extending upward from the piston **25**. Since this column is static, or nearly so, there is no friction loss and hence the pressure asserted against the top of the piston **25** is approximately pump pressure plus elevational head. At the same time, the flowing fluid in the annulus B enters the cylinder **25***a* through slots **54** below the piston **25**. Since this fluid has substantially the same elevational head, this value cancels out. That is, elevational head acts against both sides of the piston **25** and may, therefore, be disregarded. However, the pump pressure of the flowing liquid is diminished by friction losses, while that in the nearly stationary column is not. Thus, pressure asserted against the bottom of the piston **25** is increasingly less than that asserted against the top as the inner column D builds up. Ultimately, a pressure differential sufficient to overcome the spring **21** is reached and the piston **25** is forced downward to drive the valve balls **22** against their seats **22***a*. Hence, the column D is essentially a pressure differential sensor.

Actually, virtually the entire column of fluid is at all times present within the inner conduit D and only the volume displaced by the piston **25** during its upward stroke is replaced through the filter intake **31**.

In the throttle valve assembly **16**, a throttling needle valve **28** is interposed in branch line **16***a* formed in the valve body **14**. The needle valve **28** forms a restricted orifice which is adjustable as shown, in order to control the rate at which the fluid within the conduit D flows to the piston, and hence to control the period of time required for the static column to build up to a level sufficient to produce the operating stroke of the piston.

Similarly, a second needle valve **29** is provided to control the rate of upward flow of the fluid displaced by the piston when it is urged upwardly. The second needle valve thus controls the length of time for the opening movement of the valve balls **22**, and the two needle valves together determine the period of a complete cycle of operation of the device for a given set of conditions. Each of the throttle valves **28** and **29** has a one-way ball check valve **34** and **35**, respectively, in conjunction therewith, so that only one throttle valve controls flow in each direction. Thus, downward flow is blocked by the check valve **35** and upward flow is blocked by check valve **34**.

It will be seen, therefore, that the column of fluid within the inner conduit D is, in effect, moved upward as a unit by the piston **25** to be displaced above the piston, and separated from it by the throttle valve assembly **16** which permits the gradual return of the column through the needle valve **28**. Then, when the column is once more supported on the piston **25**, the pump pressure acting against it overcomes the friction-attenuated pressure of the flowing stream to force the piston down.

The operation of the circulating fluid to drive the piston downward may be illustrated in connection with typical conditions of operation. Suppose a driller is operating with 150 feet of 6½ inch O.D. by 3½ inch I.D. drill collars weighing 80 pounds per foot; he is using a roller bit of 7⅞ inch diameter; and he is circulating water as the drilling fluid at the rate of six barrels per minute. Suppose also that he has installed a differentiating tube **19** including a piston cylinder **25***a* that has an internal diameter of 2¼ inches and an outer diameter of 2⅞ inches, with the length L of the differentiating column D being 120 feet.

The area of the annulus B is:

$$\pi(D11)^2/4-\pi(D21)^2/4=9.65-6.5$$
$$=3.15 \text{ sq. inch}=3.15/144=.02185 \text{ sq. ft.}$$

With a 42 gallon barrel, the flow per second is

$$\frac{6}{60}+42 \text{ or } 4.2 \text{ gallons}$$

and the flow in cubic feet per second is

$$\frac{4.2}{7.48}=.562 \text{ cubic feet/sec.}$$

Hence, the flow velocity through the annulus is:

$$\frac{.562}{.02185}=25.7 \text{ feet/sec. (approx.)}$$

The flowing friction loss in the annulus B may be calculated by the following formula:

$$P=\frac{.094\,Q^{1.8}G^{.8}N_t{}^{.2}L}{(D-d)^3(D+d)^{1.8}}$$

where:

P=friction loss pressure in p.s.i;
Q=flow rate in bbls./min.;
G=fluid density in lb./gal.;
Nt=turbulent viscosity in centiposes;
L=length of pipe in ft.;
D=large diameter in inches; and
d=small diameter in inches

(Oil Well Drilling Technology, McCray and Cole, p. 264)

With water $Nt=1$ and $G=8.5$ lb./gal. Therefore, computing for 1 foot of length:

$$P=\frac{.094(6)^{1.8}(8.5)^{.8}\times 1^{.2}\times 1}{(3½-2⅞)3(3½+2⅞)1.8}$$

$$=\frac{.094(25.1)(5.52\times 1\times 1}{.244\times 28.1}$$

$$=\frac{13}{6.86}=1.9 \text{ p.s.i. per foot of length L}$$

With L set at 120 feet the total friction loss over the length in the annulus B is 228 p.s.i. Assuming no friction loss within the inner conduit D, this 228 p.s.i. constitutes the pressure differential across the piston **25**, and with a piston diameter of 2¼ inches the force may be calculated as follows:

$$F=pA$$
$$=3.98 \text{ in.}^2\times 228$$
$$=908 \text{ lbs.}$$

This is more than adequate to overcome a spring **21** having a compression force of 200 lbs. Because of the small clearance around the neddle valve **28** the fluid column D, and with it the piston **25**, moves down slowly, but, as described hereinabove, the pressure differential across the valve balls drives them rapidly against their seats.

When the pulse valve balls **22** are seated, the flow of mud is suddenly stopped and a pressure pulse is created in the chamber C above the drill bit **11**. Where, as here, a pressure pulse is created by suddenly closing a valve, the pressure so generated may be assumed to be approximately 60 p.s.i. per foot of extinguished velocity and, since the velocity in the annulus B was 25.7 feet per second, the pressure increase may be assumed to be approximately 1550 p.s.i. (25.7×60). The cross-sectional area of the chamber C within the bit shank is approximately that of the internal diameter of the drill collar, or 9.65 inches square (3½ inches I.D.). Therefore, with a pressure pulse of 1550 p.s.i. the increased force within the chamber C exerted downwardly against the bit is 9.65×1550 or 14,900 lbs. It should be noted that while the velocity within the chamber C is less than that of the annulus B, the higher annular velocity is used for this calculation because the pressure generated there will also move downstream into the chamber C.

The normal flowing velocity in the hole annulus E may be calculated as follows:

With a hole diameter of 7⅞ inches and a drill collar O.D. of 6½ inches, the hole annulus has an area of .3382 ft.^{2} —.2304 ft.^{2}=.1078 ft.^{2}. The velocity therefore is:

$$V=\frac{.541 \text{ cu. ft./sec.}}{1078}=5.2 \text{ ft./sec.}$$

The momentum of the drilling fluid flowing outward from the bit causes it to continue flowing downstream (toward the earth's surface) to generate a reduction of pressure of similar magnitude per foot per second of extinguished velocity. Again, assuming that the pressure reduction is 60 p.s.i. per foot of extinguished velocity, the pressure drop below the bit is 5.2×60 or 312 p.s.i. acting against a cross-sectional area which is approximately equal to that of the outer diameter of the drill collar (6½ inches). Consequently, the reduction in force under the bit is: 33.2 in.^{2}×312=10,300 lbs. Thus, the net downward pulse force asserted against the bit is equal to the increased pressure acting downward plus the reduction of pressure below it, or: 14,900 lbs. + 10,300 lbs.=25,200 lbs., compared with a normal drilling bit load of one half of the drill collar weight (150 ft. @ 80 lbs.=12,000 lbs.), or approximately 6,000 lbs. This big increase in drilling force is applied with the suddenness of a hammer blow and it is accomplished without a long string of expensive drill collars, moreover, this substantial drilling advantage is accomplished without any additional compression on the drill collars which might cause bending with subsequent drill collar failure or crooked holes.

The pulse pressure travels both upstream and downstream from the bit and, therefore, it moves upward and through the slots **54** to act against the bottom of the piston **25**. Thus, we have the generated pressure of 1550 lbs. supplemented by the force of the spring **21** opposing the previously calculated 228 p.s.i. pressure differential acting downward. This may be calculated as follows:

$$F=pA+Fs$$

assuming a spring force, Fs, of 200 pounds the total force would be:

$$F=(1550-228)\times 3.98+200$$
$$=5260+200$$
$$=5460$$

This force will drive the piston upward to commence opening of the valve as previously described, the upward movement being retarded by the needle valve **29** which restricts flow of the displaced fluid.

The pulse pressure travels both upstream and downstream through the liquid at approximately the speed of sound in water, i.e., 4200 feet per second, and it would, therefore, arrive at the top **18** of the sensor or pressure differentiating tube **19** in less than .03 seconds, the tube being 120 feet above the bit. Such pressures could cause considerable damage in the relatively thin walled drill

pipes (not shown) above the drill collar, and it is, therefore, the function of the pulse wave suppressor or dampener **17** to prevent such pressures from reaching the drill pipe.

The pressure pulse suppressor comprises a cylindrical section of cork **37** which is molded or otherwise formed on the tube **20** forming a continuation of the internal duct D. The cork may be bonded onto the tube with an elastomer and, preferably, the outer surface of the cork is covered with a thin film of the elastomer to provide a low friction surface to improve flow characteristics and to protect the cork.

The functioning of the suppressor-absorber is based on the mathematical law for pulse pressure. Marks' Mechanical Engineers' Handbook, 6th ed., p. 3–80, gives the following engineering formula for the pulse pressure generated when a valve is suddenly closed in a liquid carrying steel pipe line:

$$P=V\sqrt{\frac{w}{g}}\sqrt{E}$$

Where:

P=pressure
V=velocity
g=acceleration of gravity
w=specific weight of liquid
E=bulk modulus of the liquid

Bulk modulus of elasticity is a term to define the reciprocal of compressibility and the value of the modulus is the amount of pressure directed normally to the surfaces of the article, i.e., squeezing forces, which is required to produce a unit reduction in volume. It may be expressed by the following equation:

$$E=\frac{\text{stress}}{\text{strain}}=\frac{\frac{\Delta P}{\Delta V}}{v_1}=\frac{\Delta P V_1}{\Delta V}$$

The effect of the elasticity of the steel pipe is normally neglected in engineering work since the elastic (tension) modulus of steel is approximately 100 times the bulk modulus of water. The bulk modulus of water is constant at 300,000 p.s.i. and, therefore, the pressure generated per unit of extinguished velocity may be calculated as follows:

$$P=V\frac{W}{g}$$

$$=1\times\frac{E}{\sqrt{1.94}}\times\sqrt{300{,}000\times 144}$$

$$=9{,}150 \text{ lb./ft.}^2$$

$$=63.5 \text{ p.s.i.}$$

This would support the assumed value of 60 p.s.i. for each foot per second of quenched velocity for water flowing in a steel pipe.

From the graph of FIG. 3, it will be noted that the modulus of elasticity for cork is variable but much lower than that for water, and that the volume of cork changes up to about 3100 p.s.i., as follows:

$$V=1-.20=.80\%$$

Therefore:

$$E=\frac{3100\times 1}{.80}=3900 \text{ p.s.i. (approx.)}$$

Thus for a ratio:

$$\frac{E \text{ for water}}{E \text{ for cork}}=\frac{300{,}000}{3900}=\frac{76.1}{1}$$

With steel pipe being inelastic compared to water and cork, and with cork being fixed within the pipe so that water is the only moving substance, we have:

$$P=V\sqrt{\frac{w}{g}}\sqrt{E_{c+w}}$$

Where w/g is the mass density of the water, water being the only substance having momentum, and is the cause of water hammer. E_{c+w} is the bulk modulus of the combined cork and water, both materials being compressed indiscriminately. The expression for E_{c+w}:

$$E_{c+w}=\frac{1}{\frac{1}{\frac{E_c}{X}}\frac{1}{\frac{E_w}{1-X}}}$$

Where:

E_w=bulk modulus of water
E_c=bulk modulus of cork
X=percent by volume of cork

If cork comprises 50% of the volume within the steel pipe:

$$E_{c+w}=\frac{1}{\frac{1}{\frac{3900}{0.05}}\frac{1}{\frac{300{,}000}{0.05}}}=7810 \text{ p.s.i. or } 1{,}125{,}000 \text{ lb./ft.}^2$$

and the pressure per foot of quenched velocity:

$$P=1\sqrt{1.94}\sqrt{1{,}125{,}000}=1480 \text{ lb./ft.}^2=10.27 \text{ p.s.i.}$$

when compared to water with no cork, the ratio:

$$\frac{\text{water}}{\text{water+cork}}=\frac{63.5}{10.27}=\frac{6.18}{1}$$

Thus, if the flow velocity interrupted was 25 ft./sec., a hammer pulse of $60\times 25=1500$ p.s.i. would travel up the annulus B at the speed of sound in water. As this pulse travels upward, it progressively stops the downward flow of water at its interface. An analogy would be an infinite number of valves spaced at incremental distances up the pipe, which valves would close in sequence at a rate corresponding to the speed of sound in water. When this hammer pulse reaches the cork section **17** with 50% cork and 50% water, and the flow velocity is quenched at that level, the pressure is:

$$P=25\times 10.27 \text{ p.s.i.}=257 \text{ p.s.i.}$$

This pressure is moderate and would not cause destruction. The energy of the water's momentum is stored as strain in the much more elastic cork. FIG. 3 shows that at 1,000 p.s.i. cork will store over 180 times as much elastic strain energy as will water.

Preferably, the needle valve **29** is set to permit the piston **25** to move upward fast enough to open the ball valves **22** and relieve pressure before the pressure pulse reaches the relatively thinner drill pipe (not shown). But even if the valve opening was delayed, the pressures generated in the drill pipe would be within safe limits. With a standard drill pipe of 4½ in. O.D. and 4.00 in. I.D. the flow pass area is .0873 ft.². Hence, the velocity with the pumps delivering .561 cu. ft./sec. is:

$$V=\frac{.561}{.0873}=6.42 \text{ ft./sec.}$$

for a quenched velocity pulse pressure of:

$$60\times 6.42=386 \text{ p.s.i.}$$

Actually, the pressure would be even less than this since the pressure in the suppressor section below it has been reduced to 257 p.s.i. There would be some flow downward tending to equalize pressure and the "progressive valve" operation in the drill pipe would not be fully effective to quench velocity.

Not only does cork suppress the development of the hammer pressure, but it also absorbs the wave energy. Cork is composed of about 200 million closed cells per cu. in. and these cells are filled with air, making cork ap-

proximately 75% air. This makes cork a good sound insulator, one of its major uses. The velocity of sound in cork is quite low, about the velocity of sound in air, approximately 1400 ft./sec. As the hammer wave, reduced in pressure, travels up the narrow annulus by the absorber **17**, the low velocity cork drags behind the portion of the wave front in, and contiguous to the cork, thus distorting and warping the wave front inwardly. The portion of the wave front in the steel and contiguous thereto runs ahead of the water wave portion which still further warps the wave front inwardly. The inwardly (transverse) travelling wave components are quickly attenuated by friction and dispersion within the cork.

FIG. 4 shows a modification wherein the filter **31***a* is replaced with another piston **44**. There is no flow by the piston **25** or piston **44** unless a leak develops, and piston **44** merely moves in unison with the piston **25**. I prefer this modification with oil between the two pistons. Of course, since the only water within the inner conduit D is that above the upper piston **44**, the length L of the column must be sufficient that flow friction losses will compensate for the difference in elevation head between the water and oil columns. Both pistons carry the scraper-type piston seals to scrape any solids ahead of the piston to minimize wear and keep solids out of the throttling valves.

FIG. 4 also shows a tool to render this percussion device inoperative, if, for some reason, this is desirable The tool comprises a cylinder **45** carrying centering fins **46**. This tool has an elastomer seal **47** on the bottom to engage the top of the sensor tubing **19** and prevent fluid from entering. This tool can be dropped into the pipe at the surface and "pumped" to the bottom. Pump pressure keeps the seal **47** in sealing contact with the top of the tube **19**. The cylinder carries a spear **48** to be engaged by a female latching socket, if it is desired to recover this tool with a wire line. The tool can be made hollow to reduce its weight, should it be desired to lift it to the surface by reverse circulation of mud. FIG. 4 also shows a pressure relief valve **49** installed in the walls of the drill collar **10** as an optional safety measure.

FIG. 5 shows a modified form of the pulse generating valve wherein the inside of the bit's shank is fitted with a torus **50** having a cylindrical outer surface which is sealed with the bit's shank by an O-ring **51**. The inside of the torus is formed to a single streamlined orifice **52** designed to pass all of the drilling mud. In this modification the dash pot cylinder **24***a* with bleeder hole **33***a* carries but a single ball or hemisphere **53**, and this seats in the orifice **52**. In this modification, the ribs **38** and grooves **39** are not required, since there is no need for angular orientation.

Operation

Considering now the apparatus of FIGS. 1A and 1B in its entirety, drilling fluid is circulated down through the drill pipe (not shown) and then into the drill collar **10** through the conduit A. When it reaches the slotted intake cap **31**, the stream divides into an internal stream flowing through the central conduit D and an outer stream in the annulus B around the outside of the pressure differentiating tube **19**. The inner conduit D quickly fills so that a nearly static column extends upward from the needle valve **28** while flow in the annulus continues at the normal rate. Consequently, the outer flowing column suffers friction losses while the inner column does not. The fluid column in the internal inner conduit D moves downward against the top of the piston at a rate determined by the needle valve **28**. Since the two fluid columns are of substantially the same height, equal to the length L of the tube **19**, the static heads balance out. However, the pump pressure acting against the top of the piston is substantially the same as that at the top of the static column in the inner conduit D while the pressure of the flowing fluid in the outer column B, which acts against the bottom of the piston, is reduced by friction losses. The resultant pressure differential across the piston slowly forces the piston downward until the valve closure balls **22** approach the valve seat **22***a*. At that time, the now restricted orifices between the balls **22** and their seats create a pressure drop across the balls which drives them sharply against the seats. This closes off the bit nozzles **32** to quench velocity suddenly and creates a pressure pulse within the chamber C and produces a sharp loss of pressure outside the bit within the bore hole annulus E. The pressure pulse, particularly since opposed by a pressure drop, delivers the desired percussion blow to the formation and then commences to travel upward within the flow conduit B to act against the bottom of the piston **25**. The initial portion of the piston movement under this rising pressure pulse is absorbed by compression of the weak spring **30** to delay opening the valves **22**. Valve opening is further delayed by restricted flow of fluid displaced by the piston through the throttle valve **29**.

The pulse pressure travels up the drill collar at approximately the speed of sound in water, 4200 ft./second, to arrive at the top of the sensor tube within .03 second. When the pulse reaches the cork suppressor-absorber, it is greatly attenuated, as explained above, and energy is stored in the cork. As the pulse is absorbed in the cork section, the strained water below causes a flow into the cork section and a reduced pressure wave starts at the cork and travels downwardly. Because of the delay in opening the pulse valves **22** occasioned by throttling and by operation of the telescopic connection **24** in the piston rod, enough time is allowed for the pressure wave to reach the cork so that considerable water will be under high strain when the pulse valves **22** again open. This is desirable so that upon opening the pulse valve **22** a high velocity flow of mud will pulse through the nozzles **32** to effectively scour cuttings off the bottom of the bore hole.

Upon opening the pulse valve **22** there is an immediate resumption of flow of mud through the nozzles **32**. At first this flow is exceedingly high in velocity due to the highly strained fluid within the drill collars, as well as the below-normal pressure beneath the bit. Resumption of flow quickly dissipates the strain energy stored in the mud, pipe and cork, and normal flow follows.

This completes the cycle. The setting of the throttling needle valve **28** determines the time interval before the next cycle begins. This time interval can be as low as a few centi-seconds and as high as desired (within reason). I prefer to rotate the bit at about 30 r.p.m. and set the needle valves **28** and **29** to deliver about 3.75 pulse cycles per reveloution.

In the above example, there is a reduction of pressure in the hole annulus E of approximately 312 p.s.i., and this pressure reduction also travels as a pulse upwardly (downstream). When this pulse reaches the drill pipe with an O.D. of only 4½ inches, the normal flowing velocity in this drill pipe annulus is only 2.46 ft./sec. Therefore, the pressure reduction caused by this pulse is $60 \times 2.46 = 147$ p.s.i. which can easily be tolerated. Moreover, the pulse in the hole annulus is often reduced because the hole walls themselves are often of a material with a relatively low bulk modulus, such as clay, shale, and porous formations. Further, normal pump flow is resumed soon after the initiation of the pulse so the reduced pressure is short-lived—a matter of centi-seconds. Of course, if desired, a section of cork can be placed around the lowest length of drill pipe similar to **17** to attenuate this hole annulus pressure wave. If the formations near the bit are highly sensitive to pressure reduction, fluted drill collars can be used to increase the cross-section of the flow area and hence reduce the flowing velocity and thereby the pulse pressure. Cork can be inserted in some of the drill collar flutes to further suppress and absorb pulse variations in the hole annulus.

While this invention has been described in connection with preferred embodiments thereof, it is understood that modifications and changes therein may be made by those skilled in the art without departing from the spirit and scope of this invention as defined by the claims appended hereto.

Having described my invention, I claim:

1. Well drilling apparatus comprising:
a tubular drill string assembly, including a rotary drill bit member and a rigid tubular member carrying said drill bit at the lower end thereof for rotating said drill bit while drilling fluid is circulated down through said tubular member,
means forming a port in said drill string assembly adjacent the lower end thereof for discharge of drilling fluid into a well bore,
a valve seat around said port,
a valve closure member, and
a pressure-responsive member connected to said valve closure member and operable intermittently to move said valve closure member against said valve seat,
an elongated inner fluid conduit within said tubular member, said inner conduit being open at the top and closed at the lower end thereof by said pressure-responsive member so that pressure of near-static fluid in said inner conduit is asserted against one side of said pressure-responsive member, and
port means bringing fluid in said tubular member flowing outside of said inner conduit into communication with the other side of said pressure-responsive member.

2. The well drilling apparatus defined by claim 1 including:
a pressure dampener in said tubular member displaced above said drill bit for suppressing pressure waves generated by seating said valve closure member.

3. The well drilling apparatus defined by claim 1 including:
resilient means biasing said other side of the pressure-responsive member.

4. The well drilling apparatus defined by claim 1 wherein said pressure-responsive member is a piston slidably carried in said inner conduit member.

5. The well drilling apparatus defined by claim 1 including:
means forming a first orifice in said inner conduit to restrict flow of fluid downward to said pressure-responsive member.

6. The well drilling apparatus defined by claim 5 including:
means forming a second orifice in said inner conduit to restrict flow of fluid upward from said pressure-responsive member.

7. The well drilling apparatus defined by claim 1 including:
a pressure wave suppressor in said tubular member comprising a material having a low bulk modulus of elasticity.

8. The well drilling apparatus defined by claim 4 including:
means forming a first orifice in said inner conduit to restrict flow of fluid downward to said piston, and
means forming a second orifice in said inner conduit to restrict flow of fluid upward from said piston.

9. The well drilling apparatus defined by claim 4 including:
a telescopic connection between said piston and said valve closure member,
stop means limiting extension and retraction of said telescopic connection, and
yieldable means biasing said telescopic connection into extension.

10. The well drilling apparatus defined by claim 1 including:
flow restricting means to restrict flow in said inner conduit in opposite directions to and from said piston.

11. The well drilling apparatus defined by claim 10 including:
means for adjusting the flow capacity of said flow restricting means.

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