

Aug. 25, 1959

F. WHITTLE
WELL DRILLING APPARATUS

2,901,221

Filed Nov. 21, 1955

3 Sheets-Sheet 1

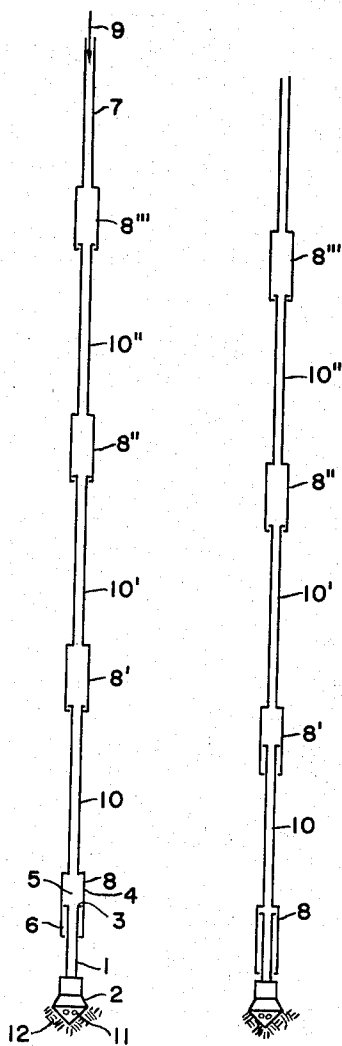


FIG. 1

FIG. 2

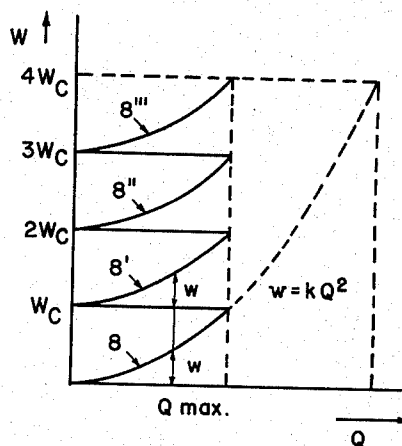


FIG. 3

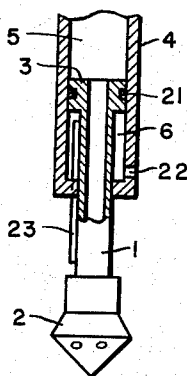


FIG. 1A

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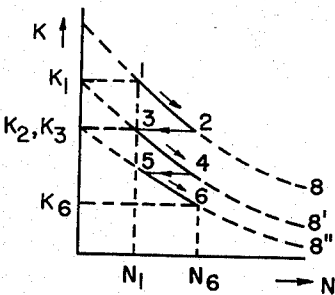
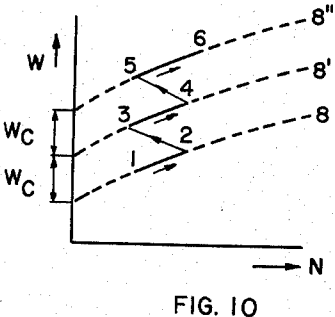
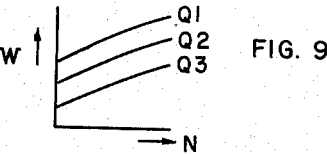
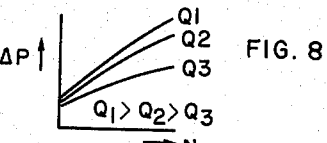
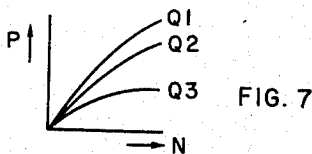
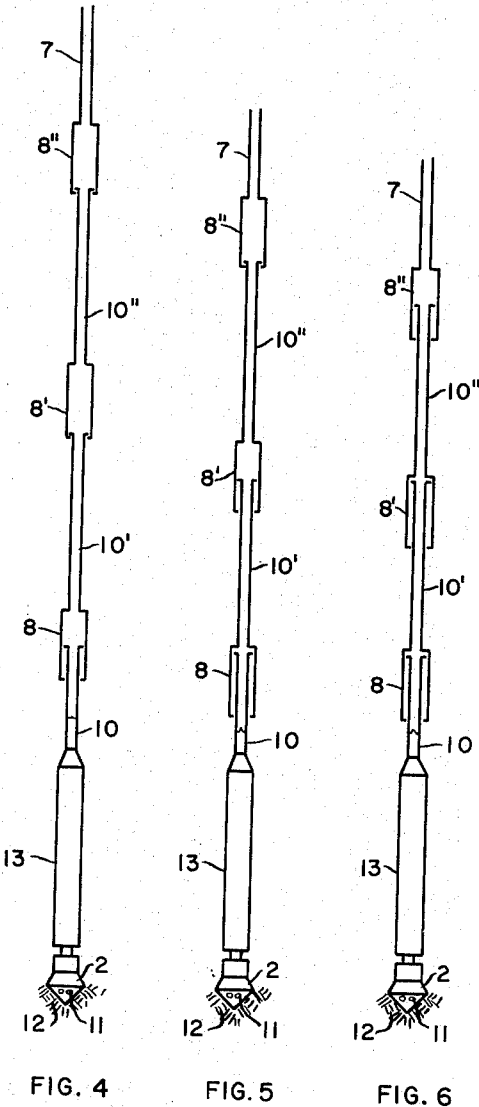
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3 Sheets-Sheet 3

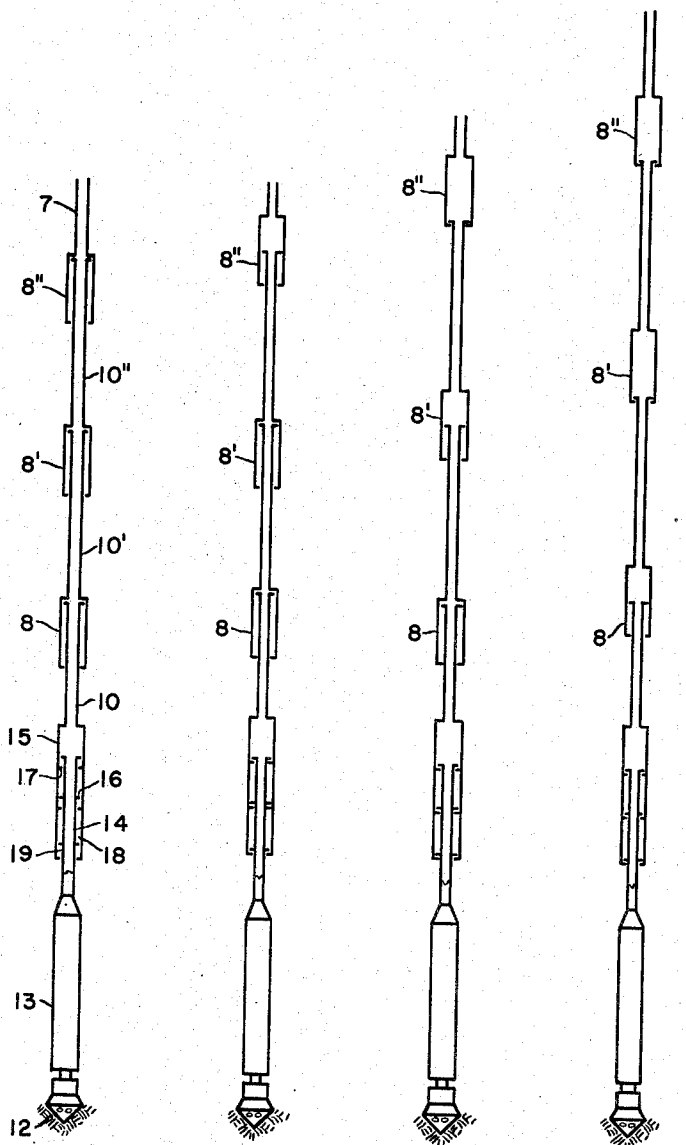


FIG. 12

FIG. 13

FIG. 14

FIG. 15

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WELL DRILLING APPARATUS

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Application November 21, 1955, Serial No. 547,988

Claims priority, application Great Britain
December 10, 1954

3 Claims. (Cl. 255—4)

The invention relates to a well drilling assembly for use with a rotary drill bit and is intended for use in drilling deep boreholes in the earth with the object of exploring the subsurface and finding mineral substances such as water, oil, gas, brine or sulphur.

More specifically, the invention relates to well drilling assemblies of the conventional type, comprising a tubular drill string to the lower end of which there is connected a rotary drill bit. The drill string is driven by a prime mover located at the top of the bore at the surface of the earth and transmits power to the bit, while a flow of mud is sent down through the interior of the drill string to the bottom of the hole. At the lower end of the drill string the mud flush is ejected through openings provided in the drill bit. The mud jets are directed onto the cutting surfaces of the bit with the object of cooling them and removing the cuttings therefrom.

The invention also relates to well drilling assemblies other than those of the conventional type mentioned above, in which assemblies the rotary drill bit is connected to the lower end of the drill string by means of an interposed driving means, such as an electric motor or a hydraulic motor such as a hydraulic turbine. When using a hydraulic turbine, it is preferably driven by the mud flush which is pumped down the hole through the drill string, which string is either kept stationary or is rotated very slowly so as to prevent sticking thereof and/or deviation of the direction of drilling. These well drilling assemblies will hereinafter be referred to as "turbo-drills."

The invention further relates to turbo-drills comprising a turbine and rotary bit, in combination with a ram device for maintaining a weight on the bit as is described in U.S. Patent 2,776,817, issued January 8, 1957 to Gregory et al.

When drilling with one of the above-mentioned assemblies, the weight on the rotating bit has to be adjusted very carefully, in order to control the rate of penetration of the bit through the formation, to avoid deviation, prevent damage to the drill collar and drill string, and, in an assembly including a motor interposed between the bit and the drill string, to keep the motor running at or near its design speed. At the same time the bit has to be advanced automatically generally under a constant bit weight.

In the specification of co-pending patent application No. 300,056, filed August 21, 1952, now Patent No. 2,776,817 issued January 8, 1957, it has been proposed to incorporate a cylinder and piston arrangement, hereinafter to be called "telescopic hydraulic sub," in the lower end of the drill string, which arrangement is actuated by the pressure differential existing between the pressure of the mud passing through the interior of the drill collars and the bore-hole pressure, and consequently exerts a load on the bit which is a function of the pressure drop across the bit jets or openings. Such a telescopic hydraulic sub consists of two mutually telescopic members

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having means preventing any rotational movement therebetween, the one telescopic member forming the cylinder, while the other telescopic member is provided with a piston. It will be obvious that by varying the circulation rate, the pressure drop across the bit jets and consequently the load on the bit can be controlled. However, in order to obtain reasonably high bit weights, and bearing in mind that the effective piston area is limited by the bore-hole diameter, the pressure drop has to be increased, either by increasing the circulation rate or by the use of a restricting flow bean located downstream of the telescopic hydraulic sub. Both cases are costly procedures in view of the waste of hydraulic horsepower.

An object of the present invention is to provide means for exerting an easily controllable load on the bit, while at the same time allowing an automatic feed of the bit over a certain depth.

According to the present invention a well drilling assembly comprising a drill string, means for supplying pressure fluid to the drill string, a rotary drill bit and a number of drill collars interposed between the drill string and the bit, is provided with at least two telescopic hydraulic subs, drill collars being mounted between the subs and above the uppermost sub.

The bit may be driven either by a surface prime mover or by a subsurface prime mover, such as a hydraulic turbine adjoining the bit.

It is a further object of the present invention to provide drilling apparatus wherein the weight on the bit may be regulated by a coarse adjustment or variation, which consists in fully extending or fully contracting the telescopic hydraulic subs successively, and by a fine variation which consists in varying the hydraulic pressure prevailing in the drill collars.

When driving the bit by means of a surface prime mover or a submerged electric motor, the said pressure variations may be obtained by varying the circulation rate of the mud flush.

When driving the bit by means of a submerged hydraulic turbine, the said pressure variations are substantially equal to the variations of the pressure drop across the turbine, which depends on the turbine speed, the circulation rate and the density of the circulating fluid.

In order to maintain a relatively narrow operating speed range for the turbine when drilling through formations having widely varying hardnesses, the circulation rate of the pressure fluid passing through the turbine may be varied, which consequently results in an additional variation of the pressure prevailing in the drill collars.

The circulation rate of the pressure fluid through the turbine may be varied manually or automatically at the top of the bore-hole, either in accordance with the bit weight, or with the turbine speed.

Extension or contraction of the telescopic hydraulic subs in succession is obtained by lifting and paying off the drill string respectively.

In addition, there may be interposed between the turbine and the drill collars a hydraulic ram device as described in U.S. Patent 2,776,817, issued January 8, 1957 to Gregory et al.

The invention will be further described with reference to illustrative embodiments thereof as shown in the accompanying drawings, in which

Figures 1 and 2 are diagrammatic vertical views of the lower end of the drill string of a rotary drilling assembly, provided with drill collars and telescopic hydraulic subs between which the drill collars are interposed.

Figure 1A is a vertical view, taken in cross section, of one type of a hydraulic sub.

Figure 3 shows the bit weight/circulation rate (W/Q) curves of the assembly according to Figures 1 and 2.

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Figures 4, 5 and 6 show diagrammatic cross sections of a turbo-drill assembly provided with drill collars and telescopic hydraulic subs between which the drill collars are interposed.

Figures 7, 8, 9, 10 and 11 respectively represent:

- The power/turbine speed (P/N) curves for various circulation rates Q of the mud-flush;
- The pressure drop/turbine speed ($\Delta P/N$) curves for various circulation rates Q of the mud-flush;
- The sub-force/turbine speed (w/N) curves for various circulation rates Q of the mud-flush,
- The bit weight/turbine speed (W/N) curves for the subs in operation respectively, and
- The formation coefficient/turbine speed (K/N) curves of the assembly shown in the Figures 4, 5 and 6.

Figures 12, 13, 14 and 15 show diagrammatic cross sections of a turbo-drill assembly combined with a hydraulic ram device, which is coupled to the drill string via drill collars and telescopic hydraulic subs, between which the drill collars are interposed.

As shown in Figure 1, the stem 1 of the rotary drill bit 2 is coupled to the piston element 3 adapted to slide in the cylinder 4. In such a cylinder-piston arrangement, hereinafter referred to as a "telescopic hydraulic sub" or a "sub", a high-pressure space 5 is sealed from a low-pressure space 6 by means of suitable sealing means 21 (Fig. 1A) provided around the piston element 3. The high-pressure space 5 is in communication with the interior of a drill string (not shown) through superposed drill collars 10, 10', 10'' and 7 and telescopic hydraulic subs 8', 8'' and 8'''. The low-pressure space 6 of each sub communicates with the bore-hole, i.e., the space outside the telescopic hydraulic sub 8, via suitable openings or ports 22 provided in the lowermost end of the cylinder 4. Any rotational movement between the piston 3 and the cylinder 4 is prevented by suitable means, e.g., by providing the piston stem with a square, polygonal or non-circular cross section and allowing it to pass through a port having a similar cross section and being located in the bottom of the cylinder 4, or by the use of suitable splines or keys 23 (Fig. 1A).

The mud-flush which is supplied under pressure at the surface of the earth to the drill string, is conducted to the bottom of the bore-hole in the direction indicated by the arrow 9 through the drill string, the telescopic hydraulic subs 8''', 8'', 8' and 8, the drill collars 7, 10'', 10' and 10, the bit stem 1 and jet openings 11 of the bit 2.

The lower end of each drill collar is connected to and in communication with the upper end of a telescopic hydraulic sub, while the upper end of each drill collar is coupled to the piston element of a superposed telescopic hydraulic sub.

It will be clear that the mud-flush pressure drop prevailing across the bit jet openings 11 will exist across each piston 3 of the telescopic hydraulic subs as well, and the force exerted by a sub will be equal to:

$$w = A \Delta p$$

where

w =force exerted by a sub

A =effective piston area of a sub

Δp =pressure differential prevailing across the piston=pressure drop across the bit jet openings.

Now the pressure drop Δp across the bit jet openings is a function of the circulation rate Q of the mud flush as follows:

$$\Delta p = k Q^2$$

where

Δp =pressure drop across the bit jet openings

k =a constant (is inter alia determined by the diameter and length of the said openings and by the viscosity and density of the mud-flush).

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It will be clear that by varying the circulation rate Q , the pressure drop Δp and consequently the force exerted by the telescopic subs in operation may be varied.

As shown in Figure 1, the bit 2 is in its active position on the bottom 12 of the bore-hole. The drill string, which is supported at its upper end by the draw-works of the drilling rig (not shown), is lifted to such an extent that the pistons of the subs 8''', 8'' and 8' are in their lower position, so that these telescopic hydraulic subs are in their extended position. The weight of the drill collars 7, 10'', 10' between the subs and part of the weight of the drill collar 10 is thus supported by the drill string. The weight of the drill collars directly above any sub should be at least as large as the force which that sub is intended to exert.

In the position shown in Figure 1, when neglecting the mass of the bit and the stem, the force w exerted by the sub 8 will provide the bit weight W , by which the bit 2 is forced against the bottom of the hole. When the bit 2 is rotated and penetrates through the formation, and the circulation rate Q and consequently the force w are kept constant, the bit 2 may penetrate over a depth equal to substantially the full stroke of the piston 3 in cylinder 4, without paying off the drill string at the surface.

In practice, it is preferable to pay off continuously at a rate approximately to the rate of penetration. It is then only necessary to adjust the rate at comparatively long intervals when there are indications that the sub in operation is either in the fully extended or fully contracted position. For example, if the surface feed were 40 feet per hour and the bit were actually penetrating at 50 feet per hour, the sub-piston would be moving downwardly in the sub-cylinder at the relative rate of 10 feet per hour. A five-foot stroke would then last 30 minutes. In reasonably uniform formations the driller can match the surface feed to the penetration rate to avoid adjustments at intervals of less than one hour, whereas if the feed were left entirely to the sub, the driller would have to pay off every few minutes.

If it is desired to increase the bit weight W the circulation rate Q may be increased. If a still higher bit weight W is required, the drill string is paid off to such an extent that the sub 8 is brought to its fully contracted position and the sub 8' is brought into operation, as shown in Figure 2. Now sub 8' plays the same role as the sub 8 shown in Figure 1 did, but the force exerted thereby is increased by the weight of W_c of the drill collar 10.

In Figure 3 the relationship between the bit weight W and the circulation rate Q is shown. Starting from the value $Q=0$, the bit weight W is equal to the sub force $w=kQ^2$. At Q_{max} the circulation is stopped and the drill string is paid off to such an extent that the sub 8' comes into action. Now the bit weight is equal to

$$W = W_c + kQ^2$$

Similarly, if the drill string is paid off further so that the sub 8'' or 8''' is brought into action, the bit weight will be given by $W=2W_c+kQ^2$ and $W=3W_c+kQ^2$ respectively.

When comparing this latter curve 8''' with the dotted extension of the curve

$$w = kQ^2$$

representing operation with only the sub 8 in use, it will be appreciated that the bit weight $4W_c$ is obtained at a much lower value of the circulation rate Q than would be the case if sub 8 were the only sub to be used.

The combination of drill collars interposed between telescopic hydraulic subs may advantageously be combined with a turbine-driven rotary bit, as is shown in Figures 4, 5 and 6, the hydraulic turbine 13 being interposed between the lowest drill collar 10 and the drill bit 2. For the sake of simplicity only three subs 8, 8' and

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8'' are shown, but it will be appreciated that, if required, the number of subs may be increased at will. As the assembly is shown in Figure 4 the sub 8 is in operation, while in Figures 5 and 6 the subs 8' and 8'' respectively are in operation.

In the following explanation of the operation of the assembly shown in Figures 4-6, the weight of the turbine 13 and the bit 2 will be neglected with respect to the weight of the drill collars 10, 10', 10'' and 7, and the pressure drop across the bit jet openings 11 will be neglected with respect to the pressure drop across the turbine 13 for the sake of simplicity.

The pressure drop Δp across the turbine is shown in Figure 8 as a function of the turbine speed N for various circulation rates Q (Q_1 being greater than Q_2 , and Q_2 being greater than Q_3). The force w exerted by a sub is shown in Figure 9 as a function of the turbine speed N for various circulation rates Q , and these curves can be represented by the formula:

$$w = A \Delta p$$

in which

w =force exerted by a sub

A =effective piston area of a sub

Δp =pressure drop across the turbine (is a function of Q).

Figure 10 shows the bit weight W as a function of the turbine speed (on a larger scale than in the Figures 7, 8 and 9) for the circulation rate Q_3 . The curves 8, 8' and 8'' represent the relationship between W and N for the subs 8, 8' and 8'' being in operation respectively.

Numerals 1 to 6 of Figure 10 are points showing the small speed range which may be employed by a turbine when hydraulic subs and drill collars are employed in the drill string. Thus, when operating the turbine at a circulation rate of Q_3 (Figure 9), the speed of the turbine may increase from numeral 1 to numeral 2 with a corresponding increase in weight on the bit. Rather than employ excessive speeds on the turbine, additional weight may be employed by contracting one of the subs so that the weight of the drill collar above the sub is also applied to the bit. This would take place at numeral 3 in Figure 10 at which time the circulation rate would be reduced. Additional weight on the bit is increased to numeral 4 by increasing the circulation rate. From numerals 4 to 5 the weight on the bit is increased by the contraction of another hydraulic sub with a decrease in circulation rate to numeral 5 which is later increased to a value represented at numeral 6.

To understand the behavior of the turbine/telescopic hydraulic subs combination under drilling conditions, it is desirable to obtain curves representing the relationship between a coefficient which is representative of the formation through which the bit is advancing, and the speed of the turbine which is loaded by the drill collars having interposed subs.

Tests indicate that the required power when drilling through a certain formation is proportional to a coefficient representative of the hardness of the formation, the bit diameter, the bit speed and the bit weight, this relationship being written as follows:

$$P = K d N W$$

in which

P =required H.P. to be delivered by the turbine

K =formation coefficient, depending on the hardness of the formation and varying from 0.0004 for hard rock to 0.001 for soft rock

d =diameter in inches of a given bit

N =rotations per minute

W =weight on bit in thousands of pounds

For a given bit d is a constant, provided there is no wear on the bit. In the formula both W and P are functions of N for various circulation rates, these functions being shown in Figures 10 and 7 respectively.

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So it is possible, as has been done in Figure 11, to draw curves (for each of the subs 8, 8' and 8'' being in operation separately) showing the relationship between the turbine speed N (on a larger scale than in the Figures 7, 8 and 9) and the formation coefficient K . From the above formula the following relationship may be derived:

$$K = \frac{P}{d N W}$$

It will be appreciated (vide Figure 11) that when drilling through a formation having a certain formation coefficient, the turbine may be operated at three different speeds when the subs 8, 8' and 8'' are put into operation respectively.

It is, however, desirable to keep the turbine speed within relatively restricted limits, as on the one hand the turbine efficiency will be maximum for the design speed of the turbine, and on the other hand overspeeding in hard formations as well as stalling of the turbine in soft formations has to be prevented. As will be explained below, it is possible to keep the turbine speed within the desired restricted limits by controlling the weight on the bit by a coarse adjustment or variation, i.e., by changing the sub which is in operation, and at the same time by a fine variation, i.e., by varying the pressure drop across the relevant sub-piston, which is automatically controlled by the turbine speed.

So when starting drilling in a soft formation (for which the high formation coefficient K_1 is representative), the turbine speed will, as shown in Figure 11, be equal to N_1 , when the telescopic hydraulic sub 8 is in operation, as shown in Figure 4. When the formation through which the bit is advancing gradually grows harder the turbine speed automatically increases to N_2 due to the fact that the drag coefficient of the bit is not as high. At this speed, the drill string 7 is paid off to such an extent that the sub 8 is fully contracted and the sub 8' is put into operation (vide Figure 5). Now drilling proceeds from point 3 (vide Figure 11) at a speed N_3 which is approximately equal to N_1 , to point 4, with the sub 8' in operation. At a speed N_4 which is approximately equal to the speed N_2 , the drill string is paid off again, so that the subs attain the position as shown in Figure 6 and drilling proceeds (provided the coefficient K is still gradually decreasing) over the course 5-6. The speeds N_5 and N_6 are approximately equal to the speeds N_1 and N_2 respectively. It will be obvious that in this way the turbine will operate in a speed range N_1 - N_6 , which is considerably smaller than the speed range which would be transversed when drilling through a formation having a formation coefficient varying from K_1 - K_6 , with a bit weight which was only determined by sub 8 in operation.

Although the drill collars of the above example all have the same weight W_c , in other embodiments of the invention these weights may be made different from each other.

In another embodiment of the invention the drill collars together with the interposed telescopic hydraulic subs are combined with the hydraulic turbine/ram device assembly as described in U.S. patent 2,776,817, issued January 8, 1957 to Gregory et al.

The ram device 2 consists, as shown, for example, diagrammatically in Figure 12, of two concentric, mutually telescopically arranged cylindrical members 14 and 15, having means to prevent any rotational movement between said members, one of the members (in the drawing, the inner telescopic member 14) being provided with a number of pistons 16 cooperating with cylinders formed by the other telescopic member (in the drawing the member 15). Annular abutments 17 separate the cylinders from each other. Each piston 16 divides the corresponding cylinder into an upper and a lower cylindrical space (18 and 19 respectively). Suitable sealing means are provided to prevent passage of

fluid between adjacent cylindrical spaces. All the upper cylindrical spaces 18 communicate with a high-pressure region, to wit the interior of the inner telescopic member 14 via ports provided in the wall thereof just above each piston, and all the lower cylindrical spaces 19 communicate with a low-pressure region, to wit the exterior of the outer telescopic member via ports provided in the wall of the member 15 just above each abutment 17.

The load on the bit is created by the pressure of the drilling mud passing through the interior of the telescopic member 14 and acting on the effective piston area in a downward direction, and is decreased by the bore-hole pressure acting on the effective piston area in an upward direction.

The pressure differential prevailing across the pistons is equal to the pressure drop across the turbine and the bit jets. As such pressure drop is a function of turbine speed, the pressure differential and consequently the bit weight is a function of the turbine speed. On the other hand, however, the bit weight exerted by the ram device influences the load on the turbine and consequently the turbine speed. It will be clear that careful consideration has to be given to the interaction between the ram device and the turbine, so as to prevent over-speeding or stalling of the latter.

The torque resistance of very soft formations may be sufficient to stall the turbine unless the bit weight is reduced sufficiently. If, in a given formation, the bit weight has to be smaller than the minimum which can be applied by the ram device, the turbine will slow down and ultimately stop.

As shown in Figure 12, the bit is penetrating through a formation 12 under normal conditions. The telescopic hydraulic subs 8, 8' and 8'' are in their contracted position and the pistons 16 are in an intermediate position. The bit weight exerted is a function of the turbine speed but it also influences the load on the turbine and consequently the turbine speed.

The subs and the ram device will be in the position as shown in one of the Figures 13 to 15, if in some kind of formation it is desired to drill with bit weights lower than the minimum which can be applied by the ram device.

These positions can be obtained from the position shown in Figure 12 by lifting the drill string until the subs 8'' and 8' are extended successively.

It will be clear that the feed of the bit is provided by the hydraulic ram device in the position as shown in Figure 12, and by the subs 8'', 8' and 8 respectively in the positions shown in the Figures 13, 14 and 15.

In all these cases the circulation rate of the mudflush may either be kept constant or varied, in which case the variations may be controlled manually in accordance with the bit weight, so as to keep the turbine speed within the required restricted limits.

I claim as my invention:

1. Well drilling apparatus through which a drilling fluid is circulated during drilling operations, said apparatus comprising a drill string adapted to be vertically positioned in a borehole, a rotary drill bit carried at the lower end of said drill string, said bit having at least one mud flush opening, motor means coupled in said drill string above said drill bit for rotating said drill bit, at least two telescopic hydraulic subs connected into said drill string adjacent said motor means, and at least one drill collar being secured in said drill string between the telescopic subs, the speed-to-bit weight ratio of said motor means being alterable by successively extending said hydraulic subs.

2. Well drilling apparatus through which a drilling fluid is circulated during drilling operations, said apparatus comprising a drill string adapted to be vertically positioned in a bore hole, a rotary drill bit carried at the lower end of said drill string, said bit having at least one mud flush opening, a hydraulic turbine coupled in said drill string and in fluid communication therewith, said turbine being actuated by a stream of drilling fluid flowing down said drill string for rotating said drill bit, at least two telescopic hydraulic subs connected into said drill string above said turbine, and at least one drill collar being secured in said drill string above each of the telescopic subs, the speed-to-bit weight ratio of said turbine being alterable by successively extending said hydraulic subs.

3. Well drilling apparatus through which a drilling fluid is circulated during drilling operations, said apparatus comprising a drill string adapted to be vertically positioned in a bore hole, a rotary drill bit carried at the lower end of said drill string, said bit having at least one mud flush opening, a hydraulic turbine coupled in said drill string and in fluid communication therewith for rotating said drill bit, a hydraulic ram device connected in said drill string above said turbine, at least two telescopic hydraulic subs connected into said drill string above said ram device, and at least one drill collar being secured above each of the telescopic subs, said hydraulic turbine and said ram device and said hydraulic subs being coaxially mounted within said drill string and operable by the flow of mud flush through the drill string, the speed-to-bit weight ratio of said turbine being alterable by successively extending said hydraulic subs.

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