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(54) WELL CONTROL

(71) We, CAMERON IRON WORKS, INC., of P.O. Box 1212, Houston, Texas, United States of America, a corporation organised and existing under the laws of the State of Texas, United States of America, do hereby declare the invention for which We pray that a Patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to the control of the pressure of fluid within a wellbore having a drill string extending into the bore.

It has been customary to provide a choke in a manifold connecting with the annulus beneath a blowout preventer closed about the drill string in order to establish and maintain a back pressure on fluid diverted through the choke which, together with the hydrostatic pressure of the mud, is sufficient to contain the pressure of fluids within formations penetrated by the wellbore—i.e., prevent them from flowing into the wellbore. In the case of a "kick", the choke must continue to contain the formation fluid as heavier mud is circulated down the drill string and up the annulus to "kill" the well. The choke is preferably adjustable so that, in controlling the well pressure, an attempt may be made to avoid establishing excessive back pressure which might cause the drill string to stick, or damage a formation, the well casing, or the wellhead equipment.

In the use of one such apparatus, when a "kick" is encountered, the preventer and choke manifold are closed, the mud pumps are stopped and shut-in pressure is observed at the manifold upstream of the choke. The pump is then started slowly as the choke is gradually opened to maintain a back pressure at a level slightly above the observed shut-in pressure. When the desired circulating rate is reached, it is held constant and the choke is continuously adjusted to maintain the pressure in a standpipe connected to the upper end of the drill string at the level it has reached at such circulating rate. The constant pressure in the standpipe is maintained until the "kick" is circulated out of the annulus.

The mud weight increase necessary to contain the formation fluid is calculated and the heavier mud is pumped into the drill string with the choke being adjusted to maintain the annulus back pressure constant. When the heavier mud reaches bottom, the user begins to adjust the choke in order to again maintain the drill string pressure constant as such mud circulates up through the annulus. Thus, in effect, the user maintains a constant bottom hole pressure by controlling the pressure in that portion of the well where the average density of the fluid in it is known more closely.

In accordance with the present invention, apparatus is provided which is not only essentially automatic in that it does not require manual adjustments of the choke, but also enables the practice of a variety of methods in that it does not require that the circulating rate be maintained constant. With such apparatus, signals are produced and delivered to the choke to automatically regulate it so that a constant bottom hole pressure is maintained.

Thus, the present invention provides apparatus for use in drilling a well into an earth formation containing fluid under pressure, wherein drilling fluid is circulated through a drill string extending into a wellbore and through the annulus therebetween, the drill string and the annulus having upper ends, one of which is an inlet and the other an outlet, there being a pressure differential, positive or negative by which the bottom hole pressure of the drilling fluid exceeds the formation fluid pressure, and there being a deviation, positive or

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negative, by which said pressure differential exceeds a predetermined value thereof. The apparatus in accordance with this invention is adapted to maintain this pressure differential at the predetermined value thereof and it comprises a choke for regulating the outlet fluid pressure in response to a bias and a control signal, means for producing a bias, and means for producing a control signal, at least one of the bias and control signal varying automatically with well characteristics, the control signal being such as to co-operate with the bias to cause the choke to increase or decrease the outlet fluid pressure in response to the deviation being respectively negative or positive, whereby the outlet pressure approaches a value at which the deviation is zero.

In the preferred embodiment, the bias is a signal "representing" the outlet pressure —that is, it is a mathematical function thereof, preferably linear. The bias signal is applied to a signal responsive operator to urge the choke member away from maximum flow-restricting position. The control signal is preferably formed by combining signals representing the inlet pressure, the static pressure, the predetermined pressure differential and the circulating pressure loss in the drill string in accordance with a mathematical function, and it is applied to the operator to urge the choke member toward maximum flow-restricting position. The control signal increases or decreases when the deviation by which the pressure differential exceeds the predetermined value thereof is respectively less or greater than zero. As the control signal increases or decreases relative to the bias signal, the choke member approaches an equilibrium position effecting an outlet pressure and thereby an inlet pressure at which the pressure differential is substantially equal to the predetermined value. By continuous regulation of the choke in this manner, the pressure differential, and consequently the bottom hole pressure, is maintained substantially constant.

It has been found that when the outlet signal is the bias, the choke will immediately respond to sudden changes in pressure of the drilling fluid at the outlet such as arise when the material constituents of the drilling fluid suddenly change. It has also been found that when the control signal is damped during its transmission to the operator, over-control and hunting may be materially reduced.

It is to be understood that "bottom hole pressure" means the pressure at the bottom of the drill string regardless of its position in the wellbore, and that the "formation pressure" when the drill string is not on bottom is adjusted to the actual position of the bottom of the drill string by reducing it by the amount of pressure due to the head of fluid between the formation and the bottom of the drill string.

It is also to be understood that while, in the preferred embodiment, the inlet for the drilling fluid is through a standpipe connected to the drill string and the outlet is through a manifold connected below the blowout preventer, the circulation may be reversed with the inlet being through the manifold and the outlet through a choke connected with the drill string.

The invention will now be described further with reference to the accompanying drawings, in which:

FIG. 1 is a diagrammatic illustration of apparatus constructed in accordance with the preferred embodiment of the invention and installed upon a typical well for controlling same;

FIG. 2 is an enlarged perspective view of the console of the apparatus in FIG. 1, as seen from one corner thereof so as to illustrate its control panel;

FIG. 3 is a diagrammatic illustration of the pneumatic-hydraulic system connecting the interior of the console with the various components of the apparatus of FIG. 1;

FIG. 4 is a schematic representation of the apparatus shown in FIG. 3;

FIGS 5 and 6 are schematic representations of alternate feedbacks to the computing relay;

FIG. 7 is a schematic representation of alternate means for operating the choke from the signals developed by the apparatus;

FIG. 8 is a schematic representation of alternate means for developing the output signal;

FIG. 9 is a diagrammatic illustration of a pneumatic system connecting the interior of a console with the various components of another embodiment of apparatus for controlling a typical well;

FIG. 10 is a detailed diagrammatic view of a switch in the pneumatic system of FIG. 9, upon movement to an alternate position;

FIG. 11 is a horizontal, sectional view of the sensor shown in connection with the apparatus of FIGS 1 to 8.

FIG. 12 is a vertical, sectional view of the sensor of FIG. 11, as seen along broken line 12---12 thereof; and

FIG. 13 is a longitudinal, sectional view of the choke.

With reference now to the details of the above-described drawings, the preferred drilling control apparatus illustrated in FIG. 1 is installed upon a well including a casing 20 lining a portion of a wellbore 21 and a casing head 22 connected to its upper end. A blowout preventer 23 connected above the casing head 22 has a bore 24 there-

through and reciprocable rams 25 mounted therein for closing the bore and shutting the well in.

A drilling bit 26 at the lower end of a drill string 27 extending through the preventer bore 24 and into the well is rotated by suitable well-known apparatus. A standpipe 28 is connected to the upper end of the drill string, and drilling mud is circulated through the standpipe, downwardly through the drill string and bit, and upwardly within annulus 29 between the drill string and the uncased and cased portions of wellbore 21.

A side outlet 30 connects with the bore of the casing head beneath the preventer. When the blowout preventer rams 25 are closed about the drill string, fluid within annulus 29 is diverted into outlet 30. Manifolding in the form of a cross 31 connecting with the outlet 30 provides a straight run from the outlet and upper and lower wings to which chokes 32 are connected. At least one of these chokes is constructed as shown in FIG. 13. The straight run and the upper and lower wings of the cross are provided with valves, whereby outlet 30 may be closed or the flow may be diverted through the straight run or either choke 32.

Choke 32 includes a flow-restricting member 33 which is urged toward and away from maximum flow-restricting position (i.e., closed or opened) by means of operator 34 in response to signals through lines 35 and 36 from console 37, in a manner to be described later in connection with FIG. 3.

As shown in FIG. 13, in its preferred form, the choke 32 includes a body 400 having a chamber 401 therein intersected by an inlet 402 to the chamber and an outlet 403 from the chamber. The inlet and outlet are formed at right angles to one another and the intersection of the inner end of the outlet 403 with the chamber 401 forms an annular seat 404 which is adapted to be substantially closed by an annular, flow-restricting member 33 which moves axially toward and away from the outlet. Thus, in the position of the flow-restricting member shown in FIG. 13, there is an annular opening between the inner end of the flow-restricting member and the inner end of the seat 404 through which fluid may pass from the inlet 402 to the outlet 403. As the member 33 moves to the left, this annular opening is, of course, enlarged so as to permit less restricted flow, in which case there is less back pressure on the annulus 29 of the well.

On the other hand, as the member 33 moves to the right, it further restricts the annular opening between its inner end and the inner end of seat 404, so as to thereby increase the back pressure in the annulus 29. In its extreme right-hand position, the inner end of member 33 moves a short distance into the inner end of the seat 404 so as to restrict flow through the choke to a maximum extent.

The operator 34 comprises a T-shaped fitting 406 having its small end removably mounted within an opening 407 in choke 400 to close same. This opening extends from the chamber to the outer end of the body in axial alignment with both the outlet 403 and the seat 404, and thus parallel to the direction of movement of member 33. Thus, in a manner to be described hereafter, the member 33 is guidably slidable within the small end of fitting 406.

The opposite large end of the fitting 406 comprises a cylinder 409 formed between a cup-shaped opening covered by a plate 408 releasably secured to and sealably engaged with the inside of the cup. A piston 410 is sealably slidable within the cylinder for reciprocation along the axis of reciprocation of the member 33, and a stem 411 extends through the fitting to connect the piston to a head on the flow-restricting member 33. Thus, reciprocation of the piston 410 of the operator will cause a corresponding reciprocation of the flow-restricting member 33 between the positions previously described.

This reciprocation of the piston results from the transmittal to its opposite sides of the signals previously described in connection with the apparatus of FIG. 1. Thus, there is a threaded port 412 in the plate 408 for connection with the line 36 shown in FIG. 3, and there is a port 412a through the cup for threaded connection with the line 35, also shown in FIG. 3.

The stem 411 has a telltale 411*a* extending sealably through the plate 408 and of the same diameter as the portion thereof extending sealably through the fitting to connect piston 410 to flow-restricting member 33. Thus, the piston 410 is balanced in this preferred embodiment of the choke 32, which is of advantage in responding to the signals. The telltale 411a is visible through a slotted guard 414 mounted about it on the outer side of plate 408 to permit the user to determine, by its movement, whether or not the choke is working properly.

The small end of the fitting is received closely within choke body 407 and is sealed with respect thereto by a seal ring 416*a*. This end of the fitting is hollow to provide a skirt 415 which extends inwardly beyond opening 407 and into the chamber 401 to a position close to the seat so as to support substantially the entire length of the flow-restricting member 33 which, as previously noted, fits closely within the inner diameter of the skirt 415 so as to be guided thereby during its reciprocation.

As can be seen from FIG. 13, the flow-restricting member 33 is hollow at its inner end opposite the passageway 403, and has a head 416 on its outer end for threaded connection to the end of the stem 411 of the operator. There are a series of ports 417 extending through the head of the member 33 to freely connect the hollow interior of the member, and thus the chamber 401, with the area between the head and the closed end of the fitting at the base of the skirt 415. In this way, pressure within the choke 32 acts only over the cross sectional area of the stem 411 to urge the flow-restricting member 33 to the left or away from flow-restricting position. Even this small force is opposed by a force due to atmospheric pressure acting on the cross sectional area of the telltale 411a, which, as previously mentioned, is of the same cross sectional area as the stem 411. Thus, there is a minimum of tendency for pressure within the choke to urge the member 33 away from flow-restriction position, particularly due to pressure within outlet 403 when the member 33 is in its extreme position within seat 404.

The seat 404 comprises a removable ring which is cylindrical so as to be reversible end-for-end within an enlarged diameter portion 403a of the outlet 403 of the choke. Thus, it is possible to increase the life of the seat by so reversing it when wear has taken place at the inner diameter of one end. The inner diameter of each end of the seat ring is chamfered to facilitate movement of the flow-restricting member 33 into its extreme flow-restricting position. A seal ring is received about a central portion of the outer diameter 418 of the ring so as to sealably engage with the recessed portion 403a in either end-for-end position of the ring.

The hollow portion of flow-restricting member 33 is recessed about its open end to receive a remoable sleeve 419, which is also cylindrical so as to be reversible end-for-end, similarly to the seat ring 404, on the hollow portion of such member. More particularly, the sleeve 419 forms a continuation of the outer diameter of the hollow portion of the flow-restricting member so as to slide with it closely within the skirt 415. The opposite ends of the outer diameter of the sleeve are chamfered for guiding into the oppositely facing end of the ring 404.

A snap ring 420 is carried within the oppositely facing grooves on the inner diameter of the ring 419 and outer diameter of the recessed portion of the member 33 so as to releasably retain the sleeve about such member body. Access is had to the snap ring 420 by means of a slot 421 extending from the end of the recessed portion of the member to accommodate a tool of any suitable type. By means of this tool, the ring may be held in collapsed position to permit insertion and removal of the sleeve 419.

The inner corners of the seat 404 and the outer corners of the sleeve 419 are lined with a hard, wear-resistant material, preferably tungsten carbide. More particularly, each such annular lining extends from an intermediate point on each end of the seat ring or sleeve to an intermediate point on the inner and outer diameter thereof, respectively. Thus the linings cover the portions of these parts which are most susceptible of wear. Furthermore, since the linings are over both corners of these parts, they serve this function regardless of how they are disposed end-for-end.

The small end of the fitting 406, including the annular skirt 415 thereof, is releasably mounted within the opening 407 of the choke body by means of snap ring 422 engaging in a groove in an outer end of opening 407. Thus, an annular shoulder about the small end of the fitting is positioned to be opposite the inner side of this groove when such end is inserted fully within the choke body opening and seal ring 416 is sealably engaged with such opening. As can be seen from FIG. 13, cover 408 is similarly releasably secured to the cup-shaped open end of the fitting, and suitable seals are provided about the openings in plate 408 and the small end of the fitting 406 so as to seal about the stem 411 connecting to the flow-restricting member 33.

As will be apparent from the foregoing, upon removal of the small end of the fitting from within opening 407, the seat ring 404 can be replaced or reversed end-for-end, therethrough. Also, of course, with the fitting removed, the sleeve 419 may also be replaced, or reversed end-for-end.

A sensor and transmitter 41 connected to outlet 30, upstream from choke 32, has line 42 leading therefrom for transmitting a signal S_o representing the outlet or choke manifold pressure to console 37, which pressure is indicated on gauge 43.

A sensor and transmitter 44 is connected to standpipe 28 for sensing the product $({}_pV^2)$ of the mud density $({}_p)$ and the square of the circulating rate (V^2), and for transmitting, through line 45 to console 37, a signal ${}_pV^2$ representing such product, which is indicated on gauge 46.

As shown in FIGS. 11 and 12, the sensing device 44 comprises a tubular conduit 425 of the same inner diameter as the standpipe 28 and having means, such as flanges, on its opposite ends for connection in the standpipe as a smooth continuation thereof. It also includes a shaft 426 extending diametrically through the opposite sides of the

conduit for rotation therein, and an arm 427 mounted on the shaft within the conduit for rotation therewith and extension longitudinally of the conduit. There is a sensing element 428 in the shape of an airfoil or hydrofoil on the end of the arm 427 remote from the shaft 426 and occupying, in a neutral position, substantially the mid portion of the conduit. More particularly, the sensing element 428 is arranged to be urged up or down out of the neutral position in proportion to the product of mud density times the square of the mud circulation rate through the conduit.

In order to reduce turbulence within the sensing device to a minimum, the arm 427 is of flat, narrow construction, as seen along the plane shown in FIG. 11, and of convergent tapering construction from the shaft 426 to the sensing element 428, as seen in the plane of FIG. 12. More particularly, the end of the arm 427 which surrounds the shaft 426 includes a teardrop portion 427a extending from one side to another of the conduit, as shown in FIG. 11, and secured to the shaft 426 by means of a set screw 431.

As shown in FIG. 11, there is also an arm 429 mounted on one outer end of the shaft 426 for rotation therewith along the outer side of the conduit 425. The end of this exterior arm 429 remote from the shaft 426 has a head 430 thereon for engagement at its lower end with an oppositely facing part on a transmitter 462 which is of such construction as to transmit a signal through line 45 proportional to the force by which the flowing drilling mud urges the sensing element 428 out of its neutral position. This force is, of course, transmitted to the head 430 through the arm 427, shaft 426, and arm 429.

The transmitter 462 is of a so-called null balance type which is operable to return the head 430 and thus the arm 429 to its original position with a force proportional to the signal which it transmits. A suitable device for this purpose is a "Nullmatic" Force Transmitter manufactured by Moore Products, Inc. Thus, in the operation of the sensing device 44, the flowing mud acts upon the element 429 to urge it out of the neutral position shown in FIG. 12 with a force proportional to the product of the mud density times the square of its circulating rate. This in turn is transmitted through the inner and outer arms to the transmitter, which in turn transmits a signal which is a mathematical function of the above-described product to the console 37.

As shown in FIG. 13, the opposite ends of the shaft 426 extend through openings 432 in sleeves 433 on opposite exterior sides of conduit 425. The inner end of each opening 432 has a shoulder 434 against which a thin disc of polytetrafluoroethylene (not shown) is held by means of a metal ring 435. A ball bearing 436 is in turn held tightly against the metal ring by means of a gland nut 437 threadedly engaged with the outer threaded end of the opening 432. The inner diameter of the PTFE disc is held tightly against the outer diameter of the shaft 426, and its inner annular portion (which may be in the order of 0.10") intermediate the inner diameter of the metal ring and the outer diameter of the shaft, is free to rotate with the shaft 426 as the sensing element 428 moves in a small arc responsive to the drilling mud flow. Thus, there is a minimum of frictional resistance to the rotation of the shaft 426, even during its small arc of rotation.

The transmitter 462 is releasably mounted upon a platform 438 suspended from the lower side of the conduit 425, as seen in FIG. 12.

Console 37 shown on a larger scale in FIG. 2 contains computing and signal-producing apparatus which will later be described in connection with particular embodiments of the invention. The console (1) computes and transmits signals to the choke operator 34, (2) provides for optional outlet (choke manifold) pressure control and (3) computes and indicates on gauge 47 the amount of mud weight increase necessary to control the well.

In performance of the first function of console 37, the outlet signal S_o is received from line 42 and transmitted through line 35 to the choke operator 34 as a bias to urge choke member 33 in opening direction. The console also computes a control signal S_c and transmits it through line 36 to the choke operator to urge member 33 in closing direction. To this end, the computer in the console first produces a signal representing the circulating pressure loss:

$$P_l = KD\,({}_pV^2) \qquad \text{(Eq. A)}$$

where K = Calibration factor
D = Length of drill string (depth)
p = Mud density
V = Circulation rate.

For many purposes, equivalent results may be obtained by combining KD into a single constant k.

The ${}_pV^2$ signal is received from line 45. Signals K and D representing the calibration factor and depth are produced by adjusting knobs 48 and 49, respectively, with the value thereof indicated on gauges 50 and 51. By multiplication, the computer produces a signal S_l representing the circulating pressure loss (KD_pV^2) and indicates same on gauge 52.

A signal S_{as} representing the shut-in static inlet pressure, adjusted by adding the pre-

determined value of the pressure differential between bottom-hole and formation pressures, positive or negative, is produced, after observation of said static pressure on gauge 40, by adjusting knob 53 and the value thereof is indicated on gauge 54. If desired, individual signals representing static pressure and pressure differential may be utilized.

The forementioned signals are combined by the computer in console 37 to produce a control signal S_c which increases as the deviation decreases and vice-versa, which is given by the equation:

$$P_d = P_i - P_l - P_{as} \quad \text{(Eq. B)}$$

where P_d = Deviation = $P_D - P'_D$
P_D = Pressure differential
P'_D = Predetermined pressure differential
P_i = Inlet pressure
P_l = Circulating pressure loss
P_{as} = Adjusted static pressure = $P_s + P'_D$

The control signal S_c increases or decreases from its base value when P_d is respectively negative or positive. This signal is transmitted to choke operator 34 through line 36 to urge choke member 33 in closing direction. Thus, the control signal cooperates with the bias whereby member 33 seeks an equilibrium position at which the deviation is zero, and the pressure differential has the predetermined value.

The second function of console 37, optional choke manifold control, is accomplished by providing a switch 59 having a lever 59*a* whereby the above control signal S_c may be replaced by the adjusted static pressure signal S_{as} to place the choke operator 34 under control of the opposing outlet pressure signal S_o in line 42.

The third function of console 37, computation of required mud weight increase, is accomplished by computer means in the console which combine the static pressure and depth signals to indicate on gauge 47 such required increase. As is well known, mud weight increase is proportional to the quotient of the static pressure and the depth of the well.

A preferred embodiment of the apparatus in which the aforementioned signals are pneumatic is shown in FIG. 3 and described therefrom. FIG. 4 may be referred to for clarification. It is understood that such signals may also be made hydraulic, electric or combinations thereof by replacing the elements described with equivalent elements well known to those skilled in the art.

A source of pneumatic pressure (not shown) supplies air through line 60, dryer 61 and filter 62. Line 60 branches into lines 60*a* and 60*b* through pressure regulators 63 and 64 to provide air at two pressures (e.g. 20 and 40 psi) for operation of the transmitters and the pneumatic devices in the console.

Transmitter 38 senses the inlet pressure and transmits a pneumatic signal S_i representing same through line 39 to gauge 40 and to computing relay 57. Transmitter 41 senses the outlet pressure and transmits a pneumatic signal S_o representing same through line 42 to gauge 43 and to hydraulic relay 65. Transmitter 44 senses ${}_pV^2$ and transmits a pneumatic signal representing same through line 45 to gauge 46 and to the section of the computer designed to produce a pneumatic signal S_l representing the circulating pressure loss, now to be described.

Said section of the computer also receives calibration factor signal K and depth signal D representing K and D in Equation A. Knob 48 adjusts regulator 48*a* to produce pneumatic signal K indicated on gauge 50. K may be determined empirically or by well-known formulas. Knob 49 adjusts regulator 49a to produce pneumatic signal D indicated on gauge 51. The K and D signals are transmitted through lines 66 and 67 to multiplying means 55 which produces signal KD. The KD and ${}_pV^2$ signals are transmitted through lines 68 and 45 to multiplying means 56 to provide the circulating pressure loss signal S_l in accordance with Eq. A. This signal is transmitted through line 69, computing relay 70 (where the signal is doubled), line 71, amplifier 72 (where the signal is quadrupled) and line 73 to gauge 52 and to computing relay 57. The signal in line 69 is weak and is therefore boosted by a factor of eight to its value in line 73.

The multiplying means 55 and 56 may be Force Bridges such as manufactured by Sorteberg Controls Company, South Norwalk, Conn., and the computing relays 57 and 70 may be Nullmatic M/F Relays-Model 68, manufactured by Moore Products Co., Spring House, Pa.

A third signal fed to computing relay 57 represents adjusted static pressure. With the well shut-in, the inlet pressure of gauge 40 is read to determine the static pressure. To this is added the predetermined value of the differential between bottom hole and formation pressures. This adjusted static pressure is set on gauge 54 by adjusting pressure regulator 53a and knob 53. The resulting signal S_{as} is transmitted to computing relay 57 through line 75. One other signal processed by relay 57 is the feed-back of control signal S_c, the purpose and function of which will be subsequently described.

Thus, computing relay 57 receives signals S_i, S_l, S_{as}, and S_c. It combines these signals

to produce an output signal S_{co}, where

$$S_{co}=S_i+S_{as}-S_i+S_o$$

If Sd is a signal pressure representing the deviation Pd, then from Eq. B

$$S_d=S_i-S_i-S_{as}, \text{ and therefore}$$

$$S_o-S_{co}=S_d \qquad \text{(Eq. C)}$$

Output control signal S_{co} is transmitted through line 76 to needle valve (or lag element) 74, and control signal S_c is transmitted from the lag element to line 77 of switch 59 which may be a three-way valve. A branch line 80 from line 77 is connected to relay 57 for the feed-back of S_o. Under dynamic conditions, there is a pressure drop across needle valve 74 depending on the direction of flow. As seen from Eq. C, when the deviation is positive, S_o is greater than S_{co}, and flow of signal air is toward the relay 57, i.e. the relay is venting S_{co} and S_o is being reduced. When the deviation is negative, flow is from relay 57 and S_o is being increased.

Thus, feed-back of signal S_o results in a controlled damping across needle valve 74, in that the system tries to maintain a pressure drop across the valve equal to S_d. This is particularly useful for low values of S_c.

From valve 59, the control signal S_o is transmitted through line 78, accumulator 79 and line 81 to hydraulic relay 65, where it opposes the outlet signal S_o transmitted to the relay through line 42 as above described. Accumulator 79 serves as further lag means and cushions the control signal. Accordingly, the feed-back of the control signal S_o to the computing relay 57, plus the damping action of the needle valve 74 and the cushioning action of the accumulator 79 minimizes overcontrol and hunting.

Means are provided whereby the user may optionally supply the substantially constant static pressure signal S_{as} to the hydraulic relay 65 in place of the control signal S_c. Thus, three-way valve 59 has another inlet to receive signal S_{as} through line 75. By moving lever 59a up or down, the user may put the choke on control signal control or on outlet pressure control. In terms commonly used in the art, this is the equivalent of putting the choke on "standpipe" or "choke manifold" control, respectively.

Hydraulic relay 65 may be a Four-Way Hydraulic Valve, Model 79, manufactured by aforesaid Moore Products Co., modified to receive two opposing pneumatic signals. It receives liquid under pressure through line 82 and exhausts liquid through line 83. It delivers liquid to one side or the other of operator 34, exhausting from the opposite side, to move the flow-restricting member 33 of choke 32 toward or away from maximum flow-restricting position as the signal in line 81, whether S_o or S_{as}, becomes greater or less than the outlet signal S_o in line 42.

Means are provided for opening the choke manually. Thus, air supply line 60b has a branch 84 through valve 85 to line 42. On opening valve 85, full supply pressure is transmitted through line 42 to relay 65. Such pressure will cause relay 65 to deliver fluid to line 35 thereby moving flow-restricting member 33 in an opening direction.

Means are provided for indicating on gauge 47 on console 37 the amount of increase in mud density required to control the increase in formation pressure. Such increase is given by the known equation:

$$P_s/.052\ D \qquad \text{(Eq. D)}$$

where P_s=static pressure
D=depth

The static pressure signal line 75 is brought to computing relay 86, where the signal is adjusted to a suitable range, and thence through line 87 to force bridge 58. The signal D representing the depth is transmitted to force bridge 58 through line 67. The bridge computes an output signal in accordance with Eq. D which signal is transmitted through line 88 to gauge 47.

In preparing to control the well with this apparatus and while drilling with the well open, the user may, from time to time, adjust knob 49 to correct depth signal D. The $_pV^2$ signal is automatically sensed and entered into the computer continuously during circulation of the mud. Thus, after adjusting for depth, the user need only compare the circulating pressure loss on dial 52 with inlet pressure on dial 40. If they are not in agreement, the user adjusts the calibration knob 48 to bring the circulating pressure loss into agreement with the inlet pressure. As previously described, change in well depth may be disregarded.

The computed circulating pressure loss takes into account the loss in the annulus as well as the loss in the drill string. While the circulating pressure loss in the annulus is relatively small and may be ignored, it may be preferable to reduce the circulating pressure loss by approximately ten percent. This may be accomplished by adjusting calibration knob 48 until the circulating pressure loss is ninety percent of the inlet pressure.

The user further prepares for the "kick" by moving switch lever 59a to standpipe control. When a "kick" is encountered, the user picks the drill but up off the bottom

of the hole, shuts down the mud pumps, and closes the blowout preventer rams 25 about the drill string 26 and opens the valve to the choke manifold. After a short wait, the inlet pressure on dial 40 and the outlet pressure on dial 43 are read and recorded. With no circulation these are static pressures. The user then sets dial 54 by means of knob 53 to indicate the static inlet pressure which was on dial 40 plus the predetermined pressure differential and starts the mud pumps. The circulating pressure loss signal S_l, the inlet pressure signal S_i and the adjusted static pressure signal S_{as} are all transmitted to computing relay 57, where together with the control signal S_c they are processed to produce output control signal S_{co}.

With the switch 59 on standpipe control, the control signal S_c is transmitted through line 78 and accumulator 79 to one side of relay 65. At the same time the outlet pressure signal S_o is transmitted by line 42 to the other side of relay 65. If control signal S_c is larger than outlet signal S_o, relay 65 will transmit pressure to operator 34 to urge the choke member in a closing direction. If outlet signal S_o is larger, the choke member will be urged in an opening direction. The operator positions the choke member so as to maintain outlet pressure at the value represented by the control signal which, in the equilibrium position, effects an outlet pressure and thereby an inlet pressure at which the pressure differential at the bottom of the drill string is substantially equal to the predetermined value. Thus, the well is controlled during the circulation out of the "kick" by maintaining the pressure differential at the bottom of the drill string constant.

If a piece of shale enters the choke and blocks the opening between the flow-restricting member and the seat, the outlet pressure will increase. Therefore, the outlet signal S_o will also immediately increase which will cause an imbalance at relay 65. However, there will be no increase in inlet pressure at this time and, therefore, there will be no change in the control signal S_c. With the outlet signal S_o being greater than the control signal S_c, the shuttle in hydraulic relay means 65 will move causing hydraulic supply to be provided to line 35 to open the choke. As soon as the shale goes through the choke, the outlet pressure will again drop and the apparatus will come back into equilibrium at the position prior to the blockage. It has been found that generally the increase in outlet pressure will be of such a temporary nature that its effect will not be transmitted to the inlet.

If, during circulation of a "kick" out of the well, there is any disturbance in well pressure values such disturbance will be reflected in the inlet circulating pressure which will in turn produce a signal change. If the inlet pressure increases, the output signal from computing relay 57 will be lowered to maintain a bias across lag element 74 which is proportional to that produced by the inlet pressure signal minus the sum of the circulating pressure loss signal and the adjusted static pressure. Thus, a small change in the inlet pressure produces a small bias across the lag element and establishes a period of time for the required change in the control signal which is in the accumulator to take place. If, on the other hand, there is a change in the circulating pressure loss signal the same chain of events will take place. Therefore, in view of the lag element 74 there will always be a gradual change in control signal S_c in response to fluctuations or changes in inlet pressure or circulating pressure loss. At the same time there will be a rapid response to changes in outlet pressure.

When the "kick" has been circulated out of the wellbore, switch 59 may be moved to choke manifold control position, and heavier mud circulated down through drill string 26 to the bottom of the hole. The added mud weight necessary in order to provide an adequate hydrostatic pressure when such mud has reached the bottom of the hole has, of course, been computed in the manner described and indicated on dial 47.

Movement of switch 59 to choke manifold control moves the valve member to the inlet position receiving the adjusted static pressure signal S_{as}. Therefore, such signal is transmitted through line 75, switch 59 and line 78 to accumulator 79 where it is transmitted by relay 65 and line 36 to the choke operator. The signal S_{as} urges the flow-restricting member toward maximum flow-restricting position. As in the case of standpipe control, the outlet pressure signal S_o is transmitted by line 42, relay 65 and line 35 to the choke operator for urging the flow-restricting member away from maximum flow-restricting position. Since the pressure in line 36 corresponds to the adjusted static pressure, this signal is a constant so that the flow-restricting member of the choke automatically adjusts in such a manner that the opposing signal through line 35, which corresponds to the outlet pressure, remains constant. This continues until the heavier mud is pumped to the bottom of the hole.

At this time, the user turns the knob 53 to change the reading on static pressure dial 54 to zero, and moves switch 59 to standpipe control. The resulting control signal is opposed by a signal corresponding to the outlet pressure transmitted through line 42 to the operator 34 through line 35. The user begins to weigh the mud returns

as soon as the outlet pressure reads zero. When the weight of the returns approaches that of the heavier mud, the user checks the hole to see if it runs over with the mud pump stopped. If it does not, he knows the well is killed.

In the event of a severe "kick", or with expensive rig rates, the user may want to start killing the well at the same time he starts to circulate the "kick" out of the annulus. In doing so, he will reduce the amount of pressure built up on the annulus, and also reduce the amount of time the drill bit is inactive.

In this latter alternative method, he follows the same initial steps as in the other method above-described when he encounters a "kick". That is, he picks the bit up off the bottom of the hole, he shuts the mud pumps down, and closes the preventer rams about the drill string. Furthermore, after the well has been shut-in for a short time, he determines the static pressure and sets the static pressure adjusted by the addition of the predetermined pressure differential. He further reads and records the outlet and inlet pressures, moves switch 59 to standpipe control position, and resumes mud circulation.

In this method, the user immediately begins to circulate the mud into the well at whatever rate he is able to mix the mud. He reads the mud weight increase on dial 47 and mixes his mud accordingly, knowing that this reading includes any overbalance he has added to the static pressure. The user determines how long it takes the new mud to get to the bit at the bottom of the drill string, and reduces the static pressure gradually so that it reaches zero when the heavier mud arrives at the bit.

As the heavier mud reaches the sensing device 44, the user observes the change in circulating pressure loss reflected on dial 52, and reduces the static pressure reading on dial 54 a corresponding amount by suitable adjustment of the knob 53. He then continues to adjust this knob in order to continuously reduce the static pressure, as adjusted, in proportion to the depth reached by the mud, until such pressure reading is zero. He also watches the outlet pressure dial 43 and when it reaches zero he knows that the well should be dead. He then begins to weigh mud returns, and when they are within a point or two of the heavier mud weight, he checks the hole to see if it will run over. If it does not, he knows that the well is dead.

Other methods may be advisable under these same or different conditions. Also, of course, the user may use this system in drilling under pressure, in which case he merely follows those procedures described in accordance with the first method during the initial standpipe control of the well.

In the preferred embodiment, the control signal S_c is fed back into the computing relay 57. However, if desired, output signal S_{co} itself may be fed back into the computing relay 57 (see Fig. 6). Fig. 5 shows another alternate means of feed back in which case the outlet pressure signal S_o is utilized. In each case, valve 74 and accumulator 79 contribute to delaying choke response, and in the case of Figure 4 the feedback also contributes to delaying choke response by controlling the bias across valve 74 until a steady state is reached, at which time $S_{co}=S_c$. This reduces "hunting" or "over-control".

While the preferred embodiment shown in FIGS. 3 and 4 utilizes hydraulic control for the operator 34, pneumatic pressure may also be used. This is shown in FIG. 7, where it can be seen that instead of feeding the outlet signal S_o and control signal S_c into hydraulic relay valve 65, the outlet signal S_o in line 42 and the control signal S_c in line 81 are fed into amplifiers 90 and 91. The amplifiers are, of course, connected to pneumatic supply pressure. The output from the amplifiers are connected to lines 35 and 36 for transmission of pneumatic pressure to the operator 34.

Also, instead of having the circulating pressure loss signal S_l and the adjusted static pressure loss S_{as} fed directly into computing relay 57, these signals may be combined in computing relay 93 and the sum thereof then fed into computing relay 94. In such case, signals will be suitably increased in value by amplifiers, see FIG. 8. Other changes in circuitry may be made in line with the basic premise that a bias is applied on one side of the operator 34 and a control signal, which is a function of the inlet pressure, circulating pressure loss and adjusted static pressure, is applied on the other side of the operator. In all cases, the choke should tend to achieve an equilibrium position which will maintain a predetermined pressure differential between the bottom hole pressure and the formation pressure with the choke being responsive to changes in inlet pressure or circulating pressure loss, so that an equilibrium position will be established which will maintain the bottom hole pressure constant.

The embodiment of the apparatus illustrated diagrammatically in FIGS. 9 and 10 is installed upon a typical well in much the same manner as the apparatus of FIGS. 1 to 8. Thus, it includes a transmitter 251 connected to the standpipe of the well for transmitting a signal through line 251a representing inlet pressure, which is indicated upon a gauge 252 disposed within and having a dial on the front panel of a console 250, which is similar in appearance to console

37 of FIG. 2. It also includes a transmitter 255 connected to the manifold of the well upstream of the choke 32 for transmitting a signal through line 255a representing outlet pressure, which is indicated on a gauge 256, also located within and having a dial on the front panel of the console. As shown in FIG. 9, each of the signal transmitting lines 251a and 255a also leads to a switch 270 within the console 250, for a purpose to be described.

The front panel of the console also includes a dial 258 for indicating the measured depth of the well in thousandths of feet, and a dial 259 adjacent the dial 258 for indicating a calibration factor. Setting of the appropriate values on these well characteristics on the dials automatically enters a signal representative of them into a computing means in the console. There is also a dial 260 for indicating the computed circulating loss of the drilling mud in pounds per square inch, which is determined in much the same manner as described above in connection with FIGS. 1 to 8.

The apparatus of FIGS. 9 and 10 also includes a sensor 261 identical to the sensor 44 described in connection with FIGS. 1 to 8 and shown in detail in FIGS. 11 and 12. It includes a transmitter 262 on one side of its conduit and a line leading therefrom for transmitting a signal representing the product of mud density times the square of its circulating rate through a gauge having a dial 269 on the front panel of the console, which indicates the value of this product.

Static pressure is observed, as in the apparatus of FIGS. 1 to 8, and its value set on dial 268 on the front panel of console 250. A desired pressure differential is added thereto so as to enter into the computing means within the console a signal representing the total.

Line 275 connecting with the gauge having dial 258 indicating the depth of the well transmits a signal representing such depth to the force bridge 276. Another line 277 transmits a signal representing the calibration factor indicated on dial 259 to the same force bridge, where these two signals are multiplied, and the product transmitted therefrom through line 278 to the force bridge 279, to which a signal representing the product of density times the square of the velocity is transmitted from sensor 261 through line 263. In this latter force bridge then, the last-mentioned signals are multiplied, and the product is transmitted as a signal representing circulating pressure loss through line 280 to the gauge 260 and through line 280a to the relay 281. A signal representing static pressure and the desired pressure differential is also transmitted to the relay 281 by means of lines 282 and 282a. In the relay 281, these signals are added, a constant is subtracted therefrom, and a signal representing their result is transmitted through line 283 to the switch 270.

Signal transmitting lines 265 and 266 are connected to the left and right-hand sides, respectively, of the piston within the operator 34 for a choke 32 identical to that above described. Thus, a signal analogous to the previously described bias of FIGS. 1 to 8 transmitted to the operator through the line 266, and another oppositely directed signal analogous to the above-described control signal is adapted to be transmitted to the left-hand side of the operator.

The switch 270 includes a valve member 271 shiftable by means of a lever 267 manipulatable from the front panel of the console, as in the case of the console 37 of FIG. 2. With the valve member positioned as shown in FIG. 9, a signal representing standpipe pressure is transmitted through line 251a to the switch and through line 272, and line 266 to the right-hand side of the choke operator 34. The signal representing the sum of circulating pressure loss and static pressure, plus a desired pressure differential, is transmitted from the relay 281 through line 283 to the switch and lines 284 and 265 to the left-hand side of the choke operator 34.

During manifold control—i.e., after the "kick" has been circulated out of the well and the heavier mud is being circulated downwardly to the bottom of the well—the switch is moved to the alternate position shown in FIG. 10. In this position, choke manifold or outlet pressure signal is transmitted through line 255a to the switch and through lines 272 and 266 to the right-hand side of the choke operator, while the signal representing static pressure plus the desired pressure differential is transmitted through line 282 to the switch and lines 284 and 265 to the left-hand side of the operator. Since this latter signal is a constant, the manifold pressure is maintained constant.

As was also the case in the apparatus of FIGS. 1 to 8, as the heavier mud begins to circulate from the lower end of the drill string up the annulus to the outlet, the switch is returned to the position of FIG. 9, and, as in the use of the apparatus of FIGS. 1 to 8, the reading on dial 268 is turned to zero, so that the control signal merely represents circulating pressure loss.

The mud weight necessary to balance or under or overbalance formation pressure is computed in a force bridge 295, which divides the static pressure times a constant by the depth of the well, a signal representing the depth of the well is transmitted to the force bridge 295 through lines 275 and 275a, and the signal representing static pres-

sure plus the desired pressure differential is transmitted through lines 282 and 282b to relay 296, which adds a constant to it, and then transmits it through line 297 to the force bridge 295. A signal representing computed mud weight is transmitted through line 298 to a gauge having a dial 299 on the front panel of the console for indicating same.

Each of the force bridges and relays are operated by an external source of supply fluid fed into the console by line 254 and then into branch lines 254a and 254b. This same source supplies pressure fluid through lines 253, 257 and 264 for operating the transmitters 251, 255 and 262 as well as other instruments of the computing means shown in FIG. 9.

The apparatus illustrated in FIGS. 9 and 10 is used in a manner which will be apparent from the description of the use of the apparatus of FIGS. 1 to 8. Thus, to summarize, with the apparatus on standpipe control, a control signal representing the sum of the circulating pressure loss and the static pressure plus the desired pressure differential is transmitted to the operator 34, and a signal representing the inlet pressure is transmitted to the operator as a bias. If the former signal is larger, the flow-restricting member of the choke is urged toward maximum flow-restricting position, which raises the outlet pressure and thus the inlet pressure. Since the signal representing inlet pressure is transmitted to the opposite side of the operator, the choke will tend to return the flow-restricting member toward an equilibrium position. On the other hand, if the bias signal is larger, the flow-restricting member will be urged away from flow-restricting position, as a result of which the outlet pressure, and thus the inlet pressure, will be decreased, whereby the choke again tends to return toward the equilibrium position. Thus, as in the case of the apparatus of FIGS. 1 to 8, the well is controlled during circulation of the kick out of the well by maintaining the pressure differential at the bottom of the drill string at the desired constant level.

Upon switching of the system to manifold control, a signal representing manifold pressure is transmitted to the operator as a bias, and a signal representing static pressure plus the desired pressure differential is transmitted thereto as a control signal. As a result, when the heavier mud is circulated downwardly through the drill string, outlet pressure is maintained constant. The user of the apparatus turns the necessary knob to reduce the reading on the static pressure dial 268 to zero, so as to prepare for switching the apparatus back to standpipe control as the mud is circulated from the lower end of the drill string up through the annulus. During this last cycle, and as in the case of the apparatus of FIGS. 1 to 8, the user begins to weigh mud returns as soon as the manifold pressure indicated on the dial 256 reads zero, and when the weight of the returns approaches that of the heavier mud, the user checks the hole to see if it runs over with the mud pump stopped. If it does not, he knows the well is killed.

This apparatus of FIGS. 9 and 10 may also be used in alternative ways, as described in connection with FIGS. 1 to 8.

WHAT WE CLAIM IS:—

1. For use in drilling a well into an earth formation containing fluid under pressure, wherein drilling fluid is circulated through a drill string extending into a wellbore and through the annulus therebetween, said string and annulus having upper ends, one of which is an inlet and the other an outlet, there being a pressure differential, positive or negative, by which the bottom hole pressure of the drilling fluid exceeds the formation fluid pressure, and there being a deviation, positive or negative, by which said pressure differential exceeds a predetermined value thereof; apparatus for maintaining said pressure differential at the predetermined value thereof, comprising a choke for regulating the outlet fluid pressure in response to a bias and a control signal, means for producing a bias, and means for producing a control signal, at least one of the bias and control signal varying automatically with well characteristics, said control signal being such as to co-operate with said bias to cause the choke to increase or decrease the outlet fluid pressure in response to said deviation being respectively negative or positive, whereby the outlet pressure approaches a value at which said deviation is zero.

2. Apparatus according to claim 1, wherein said choke has a flow-restricting member movable toward and away from maximum flow-restricting position and a signal sensitive operator for so moving the flow-restricting member.

3. Apparatus according to claim 1 or claim 2, wherein said control signal producing means includes means for sensing the inlet pressure, means for computing the pressure lost in circulation, and means for producing signals representing said pressures and the predetermined pressure differential as well as a signal representing static pressure, and means for combining said signals to produce an output signal.

4. Apparatus according to claim 3, including means for sensing outlet pressure, and means for producing an outlet signal representing the sensed outlet pressure to provide the bias.

5. Apparatus according to claim 4,

sure plus the desired pressure differential is transmitted through lines 282 and 282b to relay 296, which adds a constant to it, and then transmits it through line 297 to the force bridge 295. A signal representing computed mud weight is transmitted through line 298 to a gauge having a dial 299 on the front panel of the console for indicating same.

Each of the force bridges and relays are operated by an external source of supply fluid fed into the console by line 254 and then into branch lines 254a and 254b. This same source supplies pressure fluid through lines 253, 257 and 264 for operating the transmitters 251, 255 and 262 as well as other instruments of the computing means shown in FIG. 9.

The apparatus illustrated in FIGS. 9 and 10 is used in a manner which will be apparent from the description of the use of the apparatus of FIGS. 1 to 8. Thus, to summarize, with the apparatus on standpipe control, a control signal representing the sum of the circulating pressure loss and the static pressure plus the desired pressure differential is transmitted to the operator 34, and a signal representing the inlet pressure is transmitted to the operator as a bias. If the former signal is larger, the flow-restricting member of the choke is urged toward maximum flow-restricting position, which raises the outlet pressure and thus the inlet pressure. Since the signal representing inlet pressure is transmitted to the opposite side of the operator, the choke will tend to return the flow-restricting member toward an equilibrium position. On the other hand, if the bias signal is larger, the flow-restricting member will be urged away from flow-restricting position, as a result of which the outlet pressure, and thus the inlet pressure, will be decreased, whereby the choke again tends to return toward the equilibrium position. Thus, as in the case of the apparatus of FIGS. 1 to 8, the well is controlled during circulation of the kick out of the well by maintaining the pressure differential at the bottom of the drill string at the desired constant level.

Upon switching of the system to manifold control, a signal representing manifold pressure is transmitted to the operator as a bias, and a signal representing static pressure plus the desired pressure differential is transmitted thereto as a control signal. As a result, when the heavier mud is circulated downwardly through the drill string, outlet pressure is maintained constant. The user of the apparatus turns the necessary knob to reduce the reading on the static pressure dial 268 to zero, so as to prepare for switching the apparatus back to standpipe control as the mud is circulated from the lower end of the drill string up through the annulus. During this last cycle, and as in the case of the apparatus of FIGS. 1 to 8, the user begins to weigh mud returns as soon as the manifold pressure indicated on the dial 256 reads zero, and when the weight of the returns approaches that of the heavier mud, the user checks the hole to see if it runs over with the mud pump stopped. If it does not, he knows the well is killed.

This apparatus of FIGS. 9 and 10 may also be used in alternative ways, as described in connection with FIGS. 1 to 8.

WHAT WE CLAIM IS:—

1. For use in drilling a well into an earth formation containing fluid under pressure, wherein drilling fluid is circulated through a drill string extending into a wellbore and through the annulus therebetween, said string and annulus having upper ends, one of which is an inlet and the other an outlet, there being a pressure differential, positive or negative, by which the bottom hole pressure of the drilling fluid exceeds the formation fluid pressure, and there being a deviation, positive or negative, by which said pressure differential exceeds a predetermined value thereof; apparatus for maintaining said pressure differential at the predetermined value thereof, comprising a choke for regulating the outlet fluid pressure in response to a bias and a control signal, means for producing a bias, and means for producing a control signal, at least one of the bias and control signal varying automatically with well characteristics, said control signal being such as to co-operate with said bias to cause the choke to increase or decrease the outlet fluid pressure in response to said deviation being respectively negative or positive, whereby the outlet pressure approaches a value at which said deviation is zero.

2. Apparatus according to claim 1, wherein said choke has a flow-restricting member movable toward and away from maximum flow-restricting position and a signal sensitive operator for so moving the flow-restricting member.

3. Apparatus according to claim 1 or claim 2, wherein said control signal producing means includes means for sensing the inlet pressure, means for computing the pressure lost in circulation, and means for producing signals representing said pressures and the predetermined pressure differential as well as a signal representing static pressure, and means for combining said signals to produce an output signal.

4. Apparatus according to claim 3, including means for sensing outlet pressure, and means for producing an outlet signal representing the sensed outlet pressure to provide the bias.

5. Apparatus according to claim 4,

* C L M S *

wherein said control signal producing means includes means for damping the output signal.

6. Apparatus according to claim 5, including means for feeding said outlet signal into said signal combining means.

7. Apparatus according to claim 5, including means for feeding the control signal back into said signal combining means.

8. Apparatus according to claim 5, including means for feeding the output signal back into said signal combining means.

9. Apparatus according to any one of claims 4 to 8, wherein said choke is also selectively responsive to the static pressure signal instead of said control signal so as to cooperate with said bias to maintain said outlet pressure constant.

10. Apparatus according to claim 1 or claim 2, wherein said control signal producing means includes means for computing pressure lost in circulation, means for producing signals representing said pressure and the predetermined pressure differential as well as a signal representing static pressure, and means for combining said signals.

11. Apparatus according to claim 10, including means for sensing the inlet pressure, and means for producing a signal corresponding to said sensed inlet pressure to provide said bias.

12. Apparatus according to claim 11, including means for sensing the outlet pressure, and wherein said choke is also selectively responsive to said outlet pressure signal and said static pressure signal plus the predetermined pressure differential signal to maintain said outlet pressure constant.

13. Apparatus according to any one of claims 3 to 12, wherein the means for producing a signal representing the pressure lost in circulation includes means for sensing the product of density and the square of the circulating rate, and producing a signal which represents the sensed product.

14. Apparatus as defined in claim 13, wherein said sensing means comprises a conduit for connection in a flowline, a rotatable shaft extending through the side of the conduit, an arm mounted on the shaft within the conduit for rotation therewith and extending longitudinally of the conduit, a sensing element mounted and arranged on the end of the arm remote from the shaft for swinging out of a neutral position in proportion to MV^2, wherein M equals the density and V the velocity of a fluid flowing through the conduit, and means including a transmitter on the exterior of the conduit responsive to rotation of the arm due to swinging of the sensing element for returning the sensing element to its neutral position, said transmitter having means for producing a signal which is a mathematical function of the force necessary to so return the sensing element.

15. Apparatus for controlling the pressure of fluid within a well bore, substantially as hereinbefore described with reference to the accompanying drawings.

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