

Nov. 11, 1969

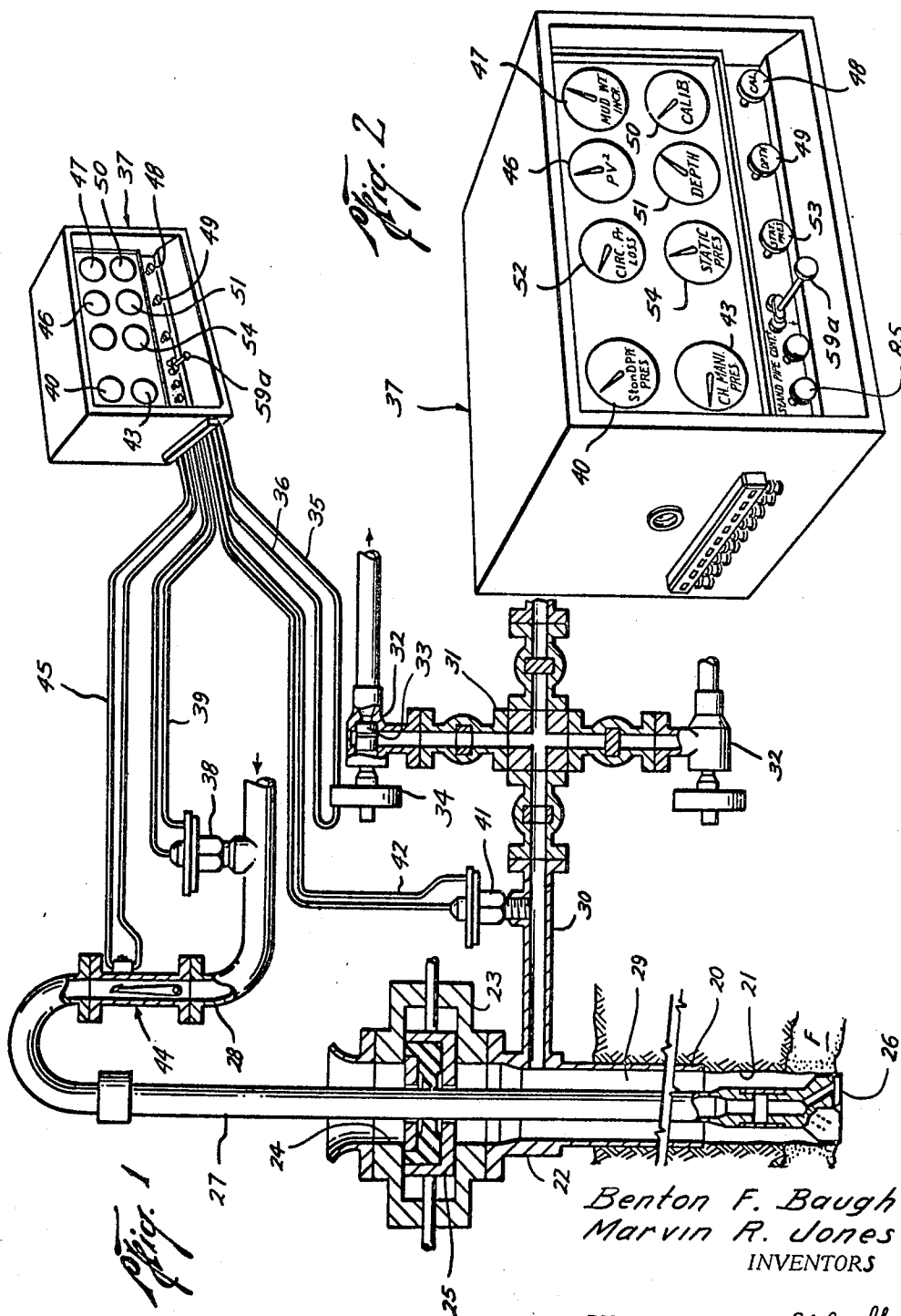
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3,477,526

APPARATUS FOR CONTROLLING THE PRESSURE IN A WELL

Filed June 7, 1967

4 Sheets-Sheet 1



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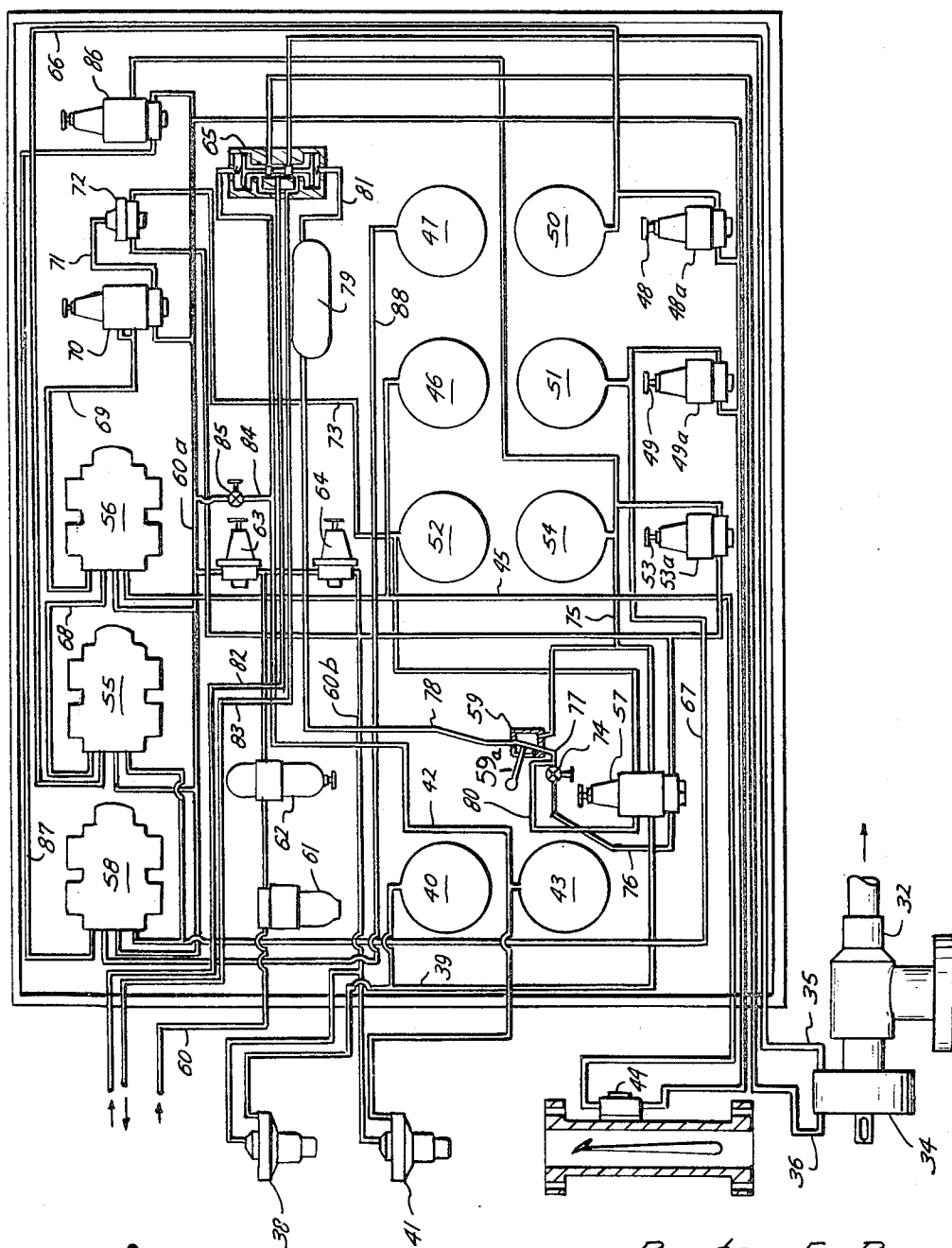


Fig. 3

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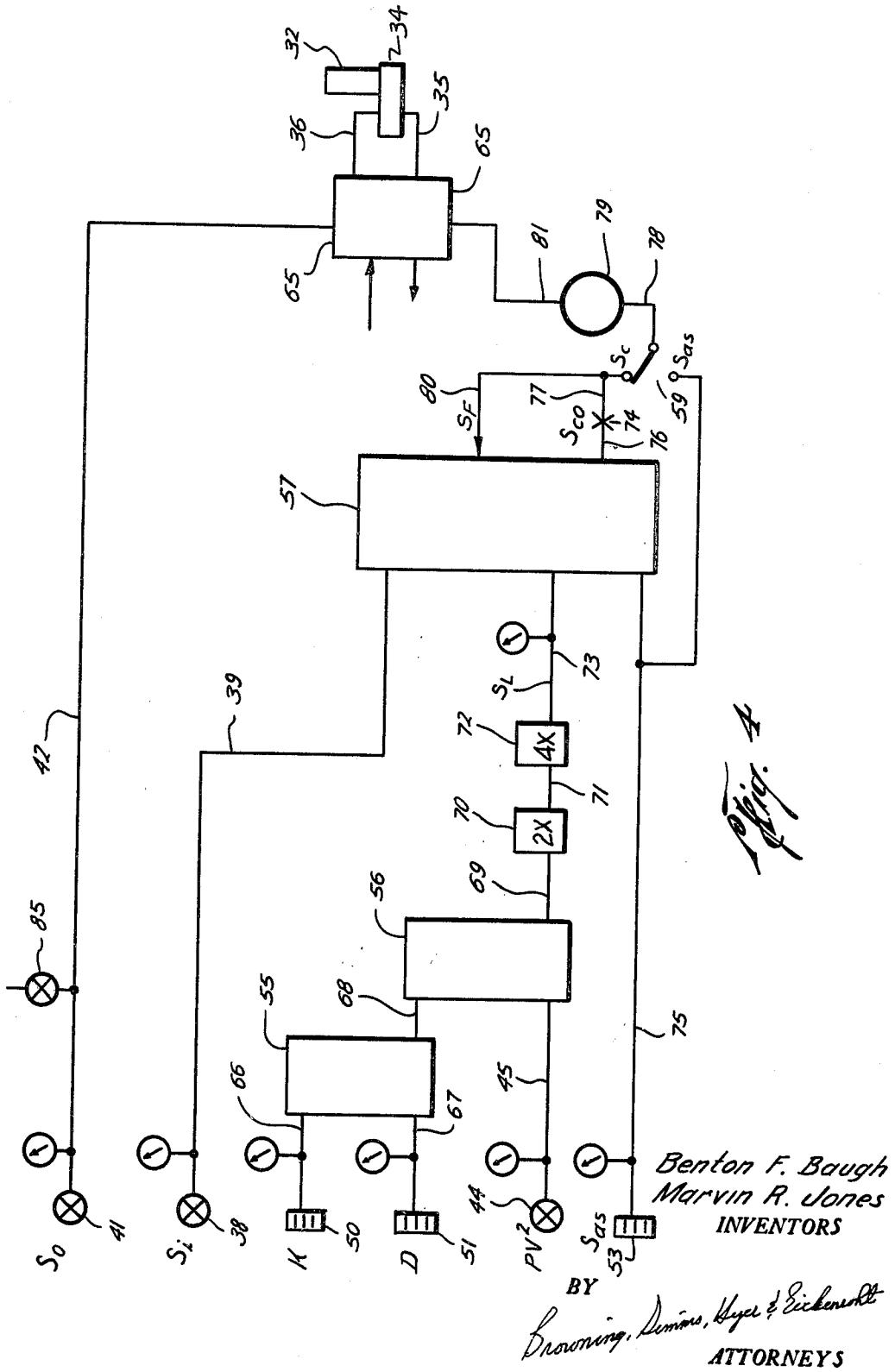
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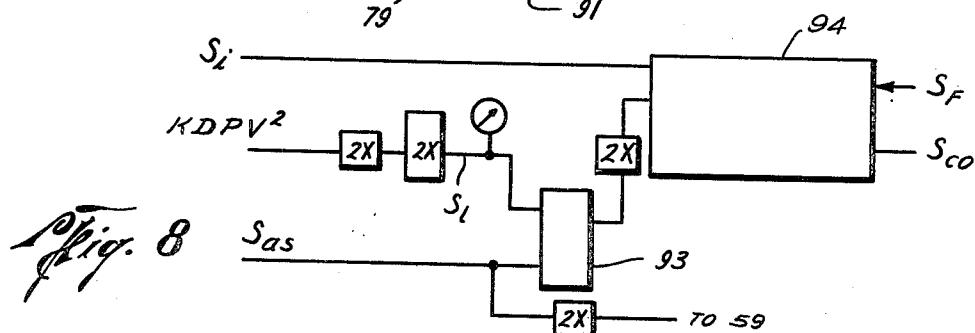
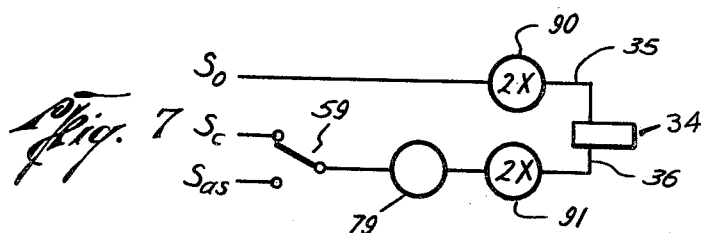
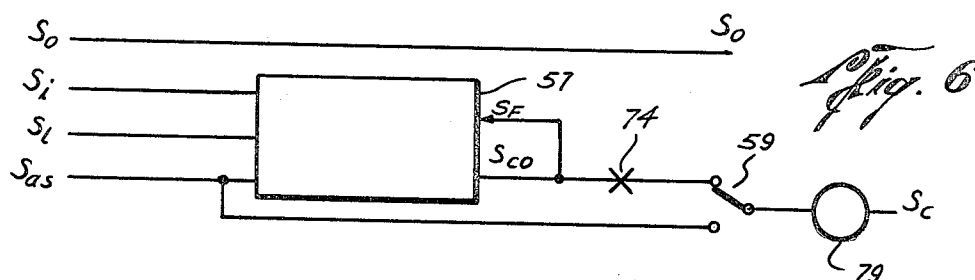
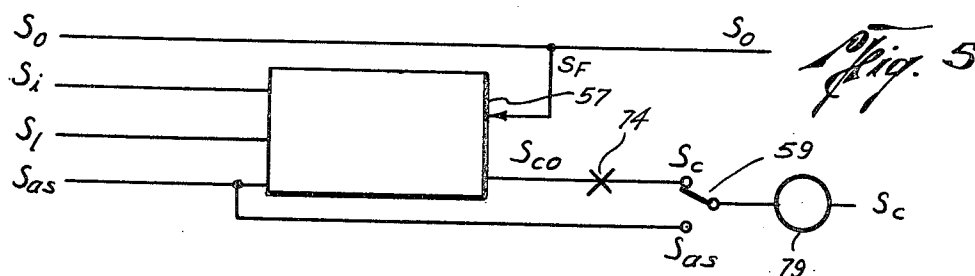
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4 Sheets-Sheet 4



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3,477,526

APPARATUS FOR CONTROLLING THE PRESSURE IN A WELL

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30 Claims

ABSTRACT OF THE DISCLOSURE

Control apparatus for use in drilling a well wherein drilling fluid is circulated through a drill string extending into a wellbore and the annulus therebetween exiting when the well is shut-in through an outlet regulated by a choke. The control apparatus maintains the pressure differential between the bottom hole pressure of the drilling fluid and the formation fluid at a predetermined value. To accomplish this, the choke is provided with signal-responsive operating means which moves a choke member toward and away from a maximum flow-restricting position in accordance with signals from the apparatus. Sensing devices at the inlet and outlet of the well measure the inlet and outlet circulating pressures and, when there is no circulation, the static pressure. A sensing device located at the inlet is responsive to the density and circulation rate of the drilling fluid. Other parameters of the well are also determined. Signals corresponding to the parameters are fed into a console having a computer which produces from the input signals a control signal which is effective to urge the choke member toward maximum flow-restricting position. A signal representing the outlet pressure is effective to urge the choke member away from the maximum flow-restricting position. The control signal and the outlet pressure signal cooperate to move the choke member to an equilibrium position at which the pressure differential is substantially equal to the predetermined value.

This invention relates to the control of the pressure of fluid within a wellbore having a drill string extending into the bore. In one of its aspects, it relates to such control upon entry of formation fluid into the drilling mud within the annulus. In another of its aspects, it relates to such control as the well is drilled under pressure. More particularly, it relates to improvements in apparatus and methods by which the well is controlled by means of a back pressure imposed on the annulus at the head of the well. In another of its aspects, it relates to novel equipment especially well-suited for such use.

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 system, 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

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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.

Our prior application Ser. No. 606,312 filed Dec. 30, 1966, now Patent No. 3,429,385 discloses a system of this general type which not only is 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 a system signals are produced and delivered to the choke to automatically regulate it so that a constant bottom hole pressure is maintained. In the preferred embodiment thereof, a signal representing the inlet pressure is applied to one side of the operator to move the choke member away from maximum flow-restricting position and another signal, representing the circulating pressure loss in the drill string plus the static pressure and a selected pressure which represents the pressure differential, is automatically computed and applied to the other side of the operator to move the choke member toward maximum flow-restricting position. These two signals cooperate to move the choke member to an equilibrium position whereby the deviation of the pressure differential from the predetermined value thereof is maintained substantially at zero and the pressure at the bottom of the drill string constant.

While such a system will control the pressure differential, it has been found that gas in the wellbore increases the time required for a pressure change at the choke manifold to travel through the wellbore and be sensed at the upper end of the drill string. This lag tends to cause undesirable "hunting" or "overcontrol" of the outlet pressure and, as a consequence, of the inlet pressure. Also, the choke is slow to respond to sudden changes in the pressure of drilling fluid at the outlet such as arise when the material constituents of such fluid suddenly change.

It is an object of the present invention to provide improved apparatus for maintaining the bottom hole pressure constant in which overcontrol due to lags in sensing pressure changes is substantially eliminated.

It is a further object to provide improved apparatus for maintaining the bottom hole pressure constant which adjusts to changes from gas to liquid flow through the choke quickly so as to avoid pressure fluctuations of significant magnitude or duration within the wellbore.

It is a further object to provide improved apparatus for maintaining the bottom hole pressure constant which utilizes an improved pneumatic computing circuit.

It is a still further object to provide methods by which these objects are attained.

These and other objects are accomplished by apparatus and methods of the present invention wherein, in preferred embodiments, the well is provided with a choke which regulates the outflow of drilling fluid when the well is shut-in. The choke is provided with a choke mem-

ber which is positioned in response to a control signal in order to increase or decrease flow restriction. The control signal may be opposed or biased by another signal or other means. For example, this bias may be a signal "representing" the outlet pressure, that is, it is a mathematical function thereof, preferably linear. The bias signal and a control signal 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 are applied to an operating means for the choke to urge the choke member toward maximum flow-restricting position when the control signal is greater than the bias signal and away from maximum flow-restricting position when the bias signal is greater than the control signal. 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 by using the outlet signal as 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 by including in the means for producing the control signal a means for damping changes thereof during its transmission to the operating means over-control and hunting are materially reduced.

It is to be understood that by "bottom hole pressure" is meant 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.

In the drawings, wherein like reference characters are used to designate like parts,

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

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

FIG. 3 is a diagrammatic illustration of a preferred pneumatic-hydraulic embodiment of the apparatus;

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

FIGS. 5 and 6 are schematics of alternate feedbacks to the computing relay;

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

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

With reference now to the details of the above-described drawings, the 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 therethrough and reciprocable rams 25 mounted therein for closing the bore and shutting the well in.

A drilling bit 26 at the lower end of drill string 27 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 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. Upon closing the blowout preventer rams 25 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. Preferably, at least one of these chokes is constructed as disclosed in said prior application. 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 operating means in response to signals through lines 35 and 36 from console 37, shown in FIGS. 1 and 2 and to be described later.

A sensor and transmitter 38 connected to standpipe 28 has line 39 leading therefrom for transmitting a signal S_1 representing the inlet or standpipe pressure to console 37, which pressure is indicated on gauge 40.

A sensor and transmitter 41 connected to outlet 30, upstream from choke 32, has line 42 leading therefrom for transmitting a signal S_0 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 (ρV^2) of the mud density (ρ) and the square of the circulating rate (V^2), and for transmitting, through line 45 to console 37, a signal ρV^2 representing such product, which is indicated on gauge 46. Sensor 44 may be such as described in said prior application.

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 member operator means, (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, and as illustrated in the preferred embodiment of the invention, the outlet signal S_0 is transmitted through line 42 to a relay 65 of the operating means to cause a related signal to be transmitted through line 35 to a reciprocable actuator 34 as a bias to urge choke member 33 in opening direction. The console also computes a control signal S_c which is transmitted through line 81 to the relay 65 to cause a related signal to be transmitted through line 36 to the reciprocable actuator to urge member 33 in closing direction.

To this end, the computer in the console first produces a signal representing the circulating pressure loss:

$$P_1 = KD(\rho V^2) \quad (\text{Eq. A})$$

where

K = Calibration factor

D = Length of drill string (depth)

ρ = Mud density

V = Circulation rate.

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

The ρV^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_1 representing the circulating pressure loss ($KD\rho V^2$) and indicates same on gauge 52.

A signal S_{as} representing the shut-in static inlet pressure, adjusted by adding the predetermined 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 is a function of the deviation, which is given by the equation:

$$P_d = P_i - P_1 - P_{as} \quad (\text{Eq. B})$$

where

P_d = Deviation = $P_D - P'_D$

P_D = Pressure differential

P'_D = Predetermined pressure differential

P_i = Inlet pressure

P_1 = Circulating pressure loss

P_{as} = Adjusted static pressure = $P_s + P'_D$.

The control signal S_c increases or decreases when P_d is respectively negative or positive and cooperates with the bias whereby choke 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 59a whereby the above control signal S_c may be replaced by the adjusted static pressure signal S_{as} to place the operating means 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 60a and 60b through pressure regulators 63 and 64 to provide air at two pressures (e.g. 20 and 40 p.s.i.) for operation of the transmitters and the pneumatic devices in the console.

Transmitter 38 senses the inlet pressure and transmits a pneumatic signal S_1 representing same through line 29 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 ρV^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_1 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 48a 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 ρV^2 signals are transmitted through lines 68 and 45 to multiplying means 56 to provide the circulating pressure loss signal S_1 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 those 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 (indicated at S_f in FIG. 4) of control signal S_c , the purpose and function of which will be subsequently described.

Thus, computing relay 57 receives signals S_1 , S_o , S_{as} , and S_c . It combines these signals to produce an output signal S_{co} , where

$$S_{co} = S_1 + S_{as} - S_1 + S_c$$

If S_d is a signal pressure representing the deviation P_d , then from Eq. B

$$S_d = S_1 - S_1 - S_{as}$$

and therefore

$$S_c - S_{co} = S_d$$

(Eq. C)

Output signal S_{co} is transmitted through line 76, needle valve (or lag element) 74, and line 77 to deliver the control signal S_c to 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_c . 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_c 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_c is being reduced. When the deviation is negative, flow is from relay 57 and S_c is being increased.

Thus, feed-back of signal S_c 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_o .

From valve 59, the control signal S_c is transmitted through line 78, accumulator 79 and line 81 to hydraulic relay 65, which, in the preferred embodiment, comprises a part of the means for operating the choke member. 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_c 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 sig-

nal 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 actuator 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 60a 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 formula:

$$P_s/.052D$$

(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 ρV^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, and thus approximately the circulating pressure loss in the drill string.

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 bit up off the bottom of the hole, shuts down the mud pumps, and closes the blow-out 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_l 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 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 actuator 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 operating means thus 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 well-bore 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 to line 78 to accumulator 78 where it is transmitted to relay 65 to urge 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 to relay 65 for urging the flow-restricting member away from maximum flow-restricting position. Since the pressure in line 81 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 42, 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. Since static pressure is zero, the signal which is transmitted to computing relay means 57 by means of line 75 is zero. Therefore, the output signal of relay 57 corresponds only to the inlet pressure minus circulating pressure loss plus the control pressure. This signal, of course, is opposed by a signal corresponding to the outlet pressure transmitted through line 42 to the relay 65. The user begins to weigh the mud returns as soon as the outlet pressure reads zero. When the weight of the returns approach 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, and the use of such methods with this system are contemplated by the present invention. 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, as indicated at S_r ; therefore the output signal S_{co} is a function of the

amount of difference in the opposing signals and there is a very gradual control signal response to changes in inlet pressure. However, if desired, the output signal S_{co} itself may be fed back into the computing relay 57, see S_r in FIG. 6, in which case the output signal will be a function of the amount of difference between the supply potential and the value of the control signal. FIG. 5 shows another alternate means of feed-back in which case the outlet signal S_o is utilized, as indicated at S_r .

While the preferred embodiment shown in FIGS. 3 and 4 utilizes hydraulic fluid for operating the actuator, 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 outputs from the amplifiers are connected to lines 35 and 36 for transmission of pneumatic pressure to the actuator 34.

Also, instead of having the circulating pressure loss signal S_l and the adjusted static pressure signal S_{as} fed directly into computing relay 57, these signals may be combined in computing relay 93 and the sum thereof then fed into a computing relay 94. In such case, signals will be suitably increased in value by amplifiers, see FIG. 8. The feed-back signal S_r shown in FIG. 4 may be S_o as in FIG. 4, S_o as in FIG. 5, or S_{co} as in FIG. 6. Other changes in circuitry in line with the basic premise that a bias is applied on one side of the operating means and a control signal, which is a function of the inlet pressure, circulating pressure loss and adjusted static pressure, is applied on the others side of the operating means may be made. 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 invention having been described, what is claimed 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 the well-bore 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 positive or negative pressure differential by which the bottom hole pressure of the drilling fluid exceeds the formation fluid pressure, the deviation, positive or negative, by which said pressure differential exceeds a predetermined pressure differential being equal to a mathematical function of the drilling fluid inlet pressure, the static pressure at the inlet when the well is shut-in, the circulating pressure loss in the drill string, and said predetermined pressure differential; apparatus for maintaining said pressure differential at the predetermined value thereof, comprising a choke for regulating the outflow of drilling fluid, said choke having a flow-restricting member movable toward and away from a position of maximum flow restriction, and operating means for so moving the flow-restricting member, said operating means being responsive to a control signal to cause the flow-restricting member to move away from maximum flow-restricting position and to a bias to cause the flow-restricting member to move toward flow-restricting position, a bias, means for sensing the inlet pressure and the static pressure, means for adjusting the static pressure by adding the predetermined pressure differential thereto, means for computing the circulating pressure loss, means for producing input signals representing said inlet pressure, adjusted static pressure and circulating pressure loss, and means for combining said input signals in accordance with said mathematical function and for producing therefrom a control signal which increases or

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decreases as said deviation becomes respectively negative or positive, whereby the flow-restricting member approaches an equilibrium position at which the outlet pressure and hence the inlet pressure are such as to effect a zero deviation with the pressure differential substantially equal to said predetermined value thereof.

2. The apparatus specified in claim 1 wherein the mathematical function controlling the deviation is as follows:

$$P_d = (P_1 - P_s - P_l - P'_D) = (P_1 - [P_s + P'_D] - P_l)$$

where

P_d is the deviation,
 P_1 is the inlet pressure,
 P_s is the static pressure,
 P_l is the circulating pressure loss,
 P'_D is the predetermined pressure differential, and
 $P_s + P'_D$ is the adjusted static pressure.

3. The apparatus specified in claim 2 wherein the means for combining the signals is a computing relay means.

4. The apparatus specified in claim 3 wherein the means for producing the control signal includes an accumulator between the relay means and the operating means.

5. The apparatus specified in claim 3 wherein the means for producing the control signal includes a needle valve.

6. The apparatus specified in claim 5 including means for feeding the control signal to the computing relay means and bypassing the needle valve so as to add it to the combination of said input signals.

7. Apparatus for use as part of a pressure control system for drilling a well, wherein a circulating medium flows through a drill string and the system includes a choke regulating the outflow of the circulating medium, the choke having a flow-restricting member movable toward and away from a maximum flow-restricting position, said apparatus comprising a console having a control panel, operating means for so moving the flow-restricting member, said operating means having first and second signal responsive sides, means in the console for automatically producing a first fluid pressure signal to be applied to the first side of the fluid pressure responsive operating means, said first signal representing the outlet circulating pressure, means in the console for automatically producing a second fluid pressure signal for selective application to the second side of the operating means, the second signal representing a function of the inlet circulating pressure, a computed circulating pressure loss, and the shut-in inlet static pressure plus a predetermined pressure differential, means in the console for automatically producing a third fluid pressure signal for selective application to the second side of the operating means, said third signal representing the shut-in inlet static pressure plus the predetermined pressure differential, and means for so selecting the second or third signal to be transmitted to the second side of the operating means, and means for transmitting said first signal and the selected second or third signal to the first and second sides, respectively, of the operating means.

8. Apparatus specified in claim 7 including a needle valve between the means for producing the second signal and the selecting means.

9. Apparatus specified in claim 8 including an accumulator between the selected means and the second side of the operating means.

10. Apparatus specified in claim 7 including a source of fluid pressure, means for connecting the source with the means for transmitting the first signal to the operating means, a valve in the connecting means, said valve being normally closed, the opening of said valve delivering fluid pressure to the transmitting means to cause the choke to open.

11. Apparatus specified in claim 7 wherein the operating means comprises an actuator for connection to the

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choke member, a source of hydraulic fluid pressure, and a relay for controlling the flow of said hydraulic fluid to and from said actuator in response to said signals.

12. Apparatus for use as part of a pressure control system for drilling a well, wherein a circulating medium flows through a drill string and the system includes a choke having a flow-restricting member for regulating the outflow of the circulating medium, said apparatus comprising choke operating means, a source of energy, means to automatically modulate said source of energy to produce a first signal representing the outlet pressure, means to automatically modulate said source of energy to produce a second signal representing the circulating pressure within the inlet end of the well, a computed circulating pressure loss within the well, and the shut-in static pressure of the well when shut-in plus a predetermined pressure differential, and means for transmitting said first and second signals to the operating means, said first signal being applied to operating means to cause the flow-restricting member to be biased away from the maximum flow-restricting position and said second signal being applied to the operating means to automatically cause the flow-restricting member to be moved toward maximum flow-restricting position when the sum of the computed circulating pressure loss and the static pressure plus the predetermined pressure differential is greater than the inlet circulating pressure, and to automatically cause the flow-restricting member to be moved away from maximum flow-restricting position when the inlet circulating pressure is greater than the sum of the computed circulating pressure loss and the static pressure plus the predetermined pressure differential.

13. The apparatus specified in claim 12 wherein the source of energy is pneumatic fluid.

14. The apparatus specified in claim 13 wherein the means for automatically computing the circulating pressure loss comprises means to modulate the pressure of the pneumatic fluid to independently produce a first signal representing the density of a circulating medium and the square of its circulating rate (ρV^2), a second signal representing the depth of the well (D), and a third signal representing a calibration factor (K), and means to combine said first three signals to compute a signal representing circulating pressure loss (P_l) by the equation

$$P_l = KD\rho V^2$$

15. 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 choke means for regulating the outlet fluid pressure to a bias signal and a control signal, means for sensing the drilling fluid outlet pressure and producing a bias signal corresponding to said sensed pressure, and means for producing a control signal which in cooperation with the bias signal causes the choke means to increase or decrease the outlet fluid pressure when said deviation is respectively negative or positive, whereby the outlet pressure approaches a value at which said deviation is zero.

16. The apparatus specified in claim 15, wherein the means for producing the control signal includes a means for damping changes therein.

17. 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 control signal and a bias, means providing a bias, and means for producing a control signal which cooperates with the bias to cause the choke to increase or decrease the outlet pressure automatically in response to said deviation being respectively negative or positive, whereby the outlet pressure approaches a value at which said deviation is zero, said last-mentioned means including means for damping changes in the control signal.

18. 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 the well-bore and through the annulus therebetween, said string and annulus having upper ends, one of which is an inlet and the other an outlet, the pressure differential by which the bottom hole pressure of the drilling fluid exceeds the formation fluid pressure being equal to a mathematical function of the drilling fluid inlet pressure, the inlet static pressure when the well is shut-in and the circulating pressure loss in the drill string; apparatus for maintaining said pressure differential at a predetermined value, comprising a choke for regulating the outflow of the drilling fluid, said choke having a flow-restricting member movable toward and away from a maximum flow-restricting position, and operating means for so moving the flow-restricting member in response to a bias signal and a control signal, means for sensing the drilling fluid outlet pressure and producing a bias signal corresponding to said outlet pressure which is effective to urge the flow-restricting member away from maximum flow-restricting position, means for sensing said inlet pressure and static pressure, means for computing circulating pressure loss, means for producing input signals corresponding to said sensed and computed pressures and a signal corresponding to said predetermined value of the pressure differential, and means combining said input signals in accordance with said mathematical function to produce a control signal which increases or decreases when the function, and thus the pressure differential, is respectively less or greater than said predetermined value, and is effective to urge the flow-restricting member toward maximum flow-restricting position, said control signal cooperating with said bias signal to move the flow-restricting member toward or away from maximum flow-restricting position as the control signal respectively increases or decreases relative to the bias signal, whereby the flow-restricting member approaches an equilibrium position effecting an outlet pressure, and thereby an inlet pressure, at which the pressure differential is substantially equal to said predetermined value thereof.

19. Apparatus as in claim 18, including means for selectively rendering said operating means responsive to said first mentioned control signal or a second control signal equal to said signal corresponding to static pressure.

20. The apparatus as in claim 18, wherein the mathematical function to which the pressure differential is equal is:

$$P_d = f(P_i - P_s - P_l)$$

where

P_d is the pressure differential,

P_i is the inlet pressure,

P_s is the static pressure, and

P_l is the circulating pressure loss.

21. The apparatus as in claim 18, wherein the means for producing the control signal includes a means for damping changes in the control signal.

22. 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 the well-bore and through the annulus therebetween, said string and annulus having upper ends, one of which is an inlet and the other an outlet, the pressure differential by which the bottom hole pressure of the drilling fluid exceeds the formation fluid pressure being equal to a mathematical function of the drilling fluid inlet pressure, the inlet static pressure when the well is shut-in and the circulating pressure loss in the drill string; apparatus for maintaining said pressure differential at a predetermined value, comprising a choke for regulating the outflow of the drilling fluid, said choke having a flow-restricting member movable toward and away from a maximum flow-restricting position, and operating means for so moving the flow-restricting member in response to a bias signal and a control signal, means for producing a bias signal which is effective to urge the flow-restricting member away from maximum flow-restricting position, means for sensing said inlet pressure and static pressure, means for computing circulating pressure loss, means for producing input signals corresponding to said sensed and computed pressures and a signal corresponding to said predetermined value of the pressure differential, and means combining said input signals in accordance with said mathematical function to produce a control signal which increases or decreases when the function, and thus the pressure differential, is respectively less or greater than said predetermined value, and is effective to urge the flow-restricting member toward maximum flow-restricting position, said control signal cooperating with said bias signal to move the flow-restricting member toward or away from maximum flow-restricting position as the control signal respectively increases or decreases relative to the bias signal, whereby the flow-restricting member approaches an equilibrium position effecting an outlet pressure, and thereby an inlet pressure, at which the pressure differential is substantially equal to said predetermined value thereof, said last-mentioned means including means for damping changes in the control signal.

23. The apparatus as in claim 22, wherein the means for producing the control signal comprises a source of supply pressure, relay means for delivering supply pressure to the operating means when the algebraic sum of the circulating pressure loss, plus the shut-in static pressure, plus the predetermined pressure differential is greater than the inlet pressure, and exhausting pressure from the operating means when the inlet pressure is greater than the algebraic sum of the circulating pressure loss, plus shut-in static pressure, plus the predetermined pressure differential.

24. The apparatus as in claim 23, including means for combining and introducing the static pressure and the pressure differential into the relay as a single signal.

25. The apparatus as in claim 23, wherein the damping means includes an accumulator between the relay means and the operating means.

26. The apparatus as in claim 23, wherein the damping means includes a needle valve between the relay means and the operating means.

27. The apparatus as in claim 26, wherein the means for producing the control signal includes means for feeding the signal between the needle valve and the operating means back into the relay means, so as to add it to said algebraic sum.

28. The apparatus as in claim 26, wherein the means for producing the control signal includes means for feeding the signal between the relay means and the needle valve back into the relay means, so as to add it to said algebraic sum.

29. The apparatus as in claim 26, wherein the means for producing the control signal includes means for feeding the bias signal into the relay means, so as to add it to said algebraic sum.

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30. The apparatus as in claim 26, wherein the damping means also includes an accumulator between the needle valve and the operating means.

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