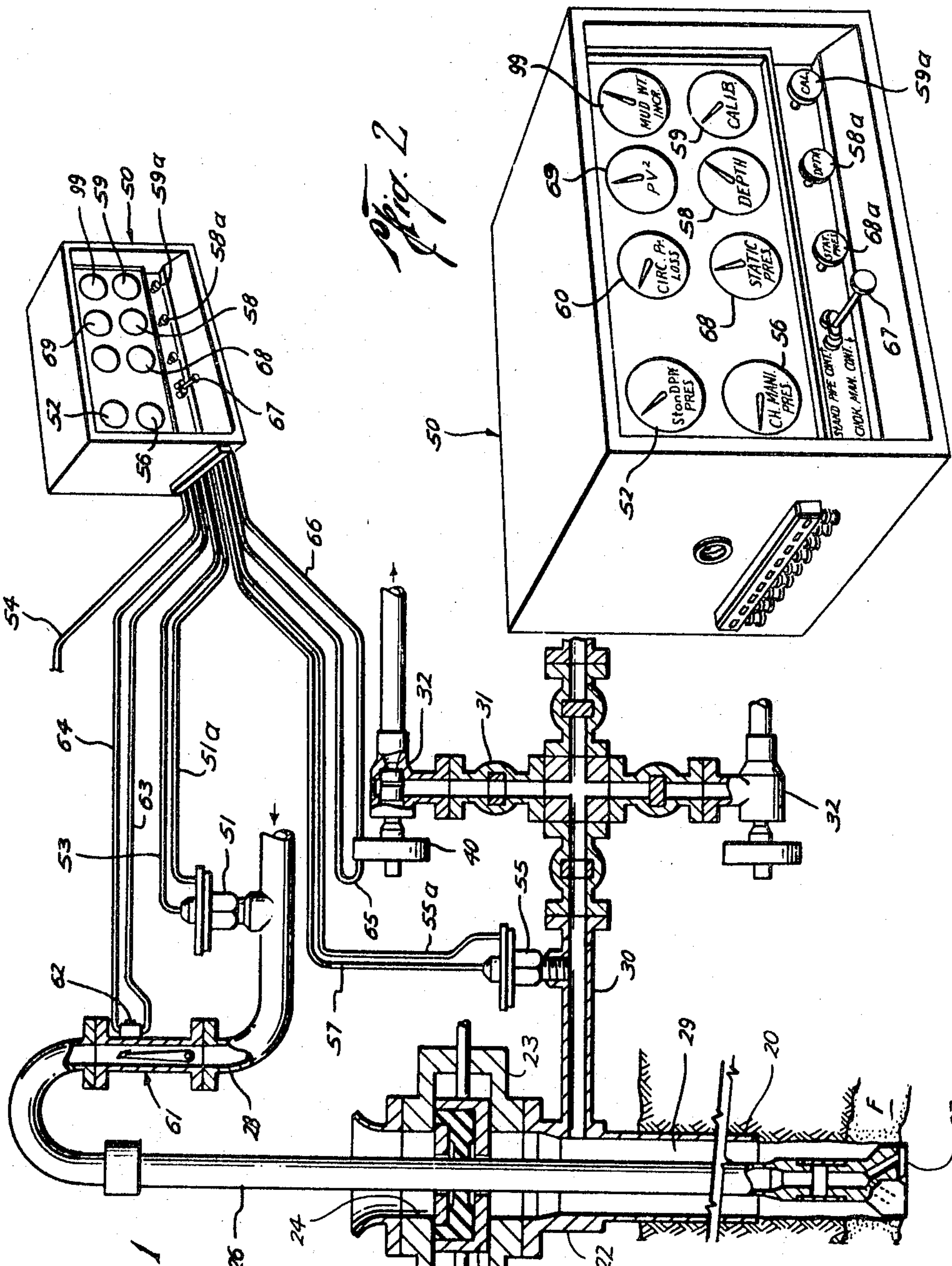
Feb. 25, 1969 M. R. JONES ET AL 3,429,385

APPARATUS FOR CONTROLLING THE PRESSURE IN A WELL

Filed Dec. 30, 1966



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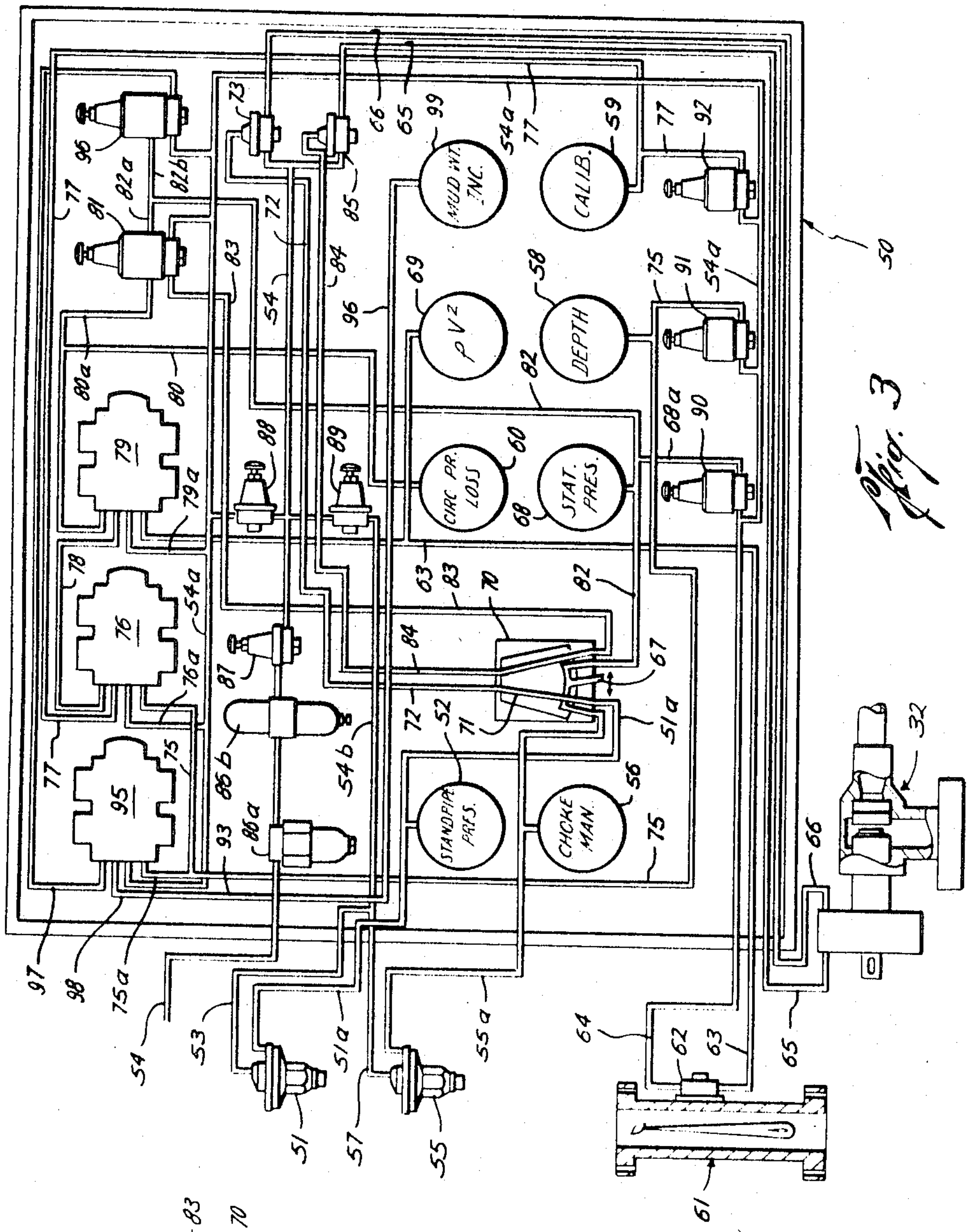

Fig. 3

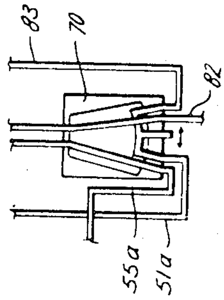

Fig. 4

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Fig. 6

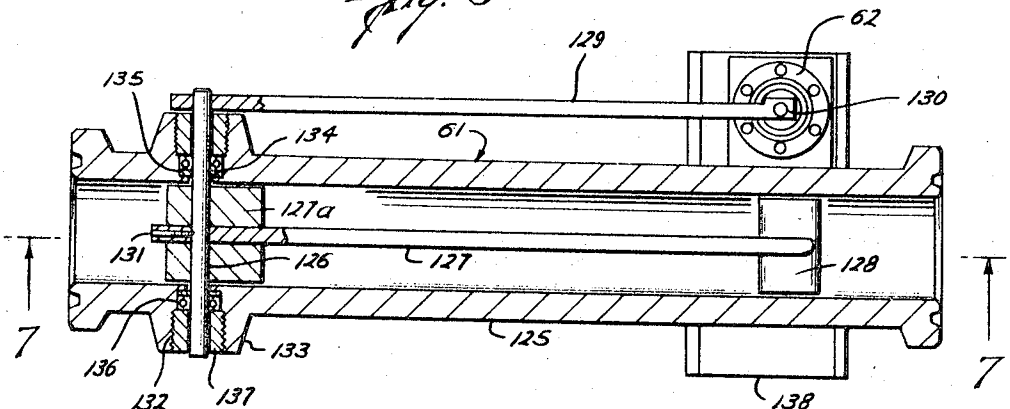


Fig. 7

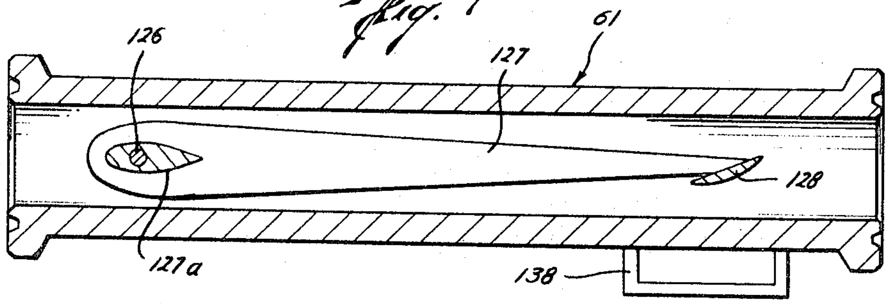
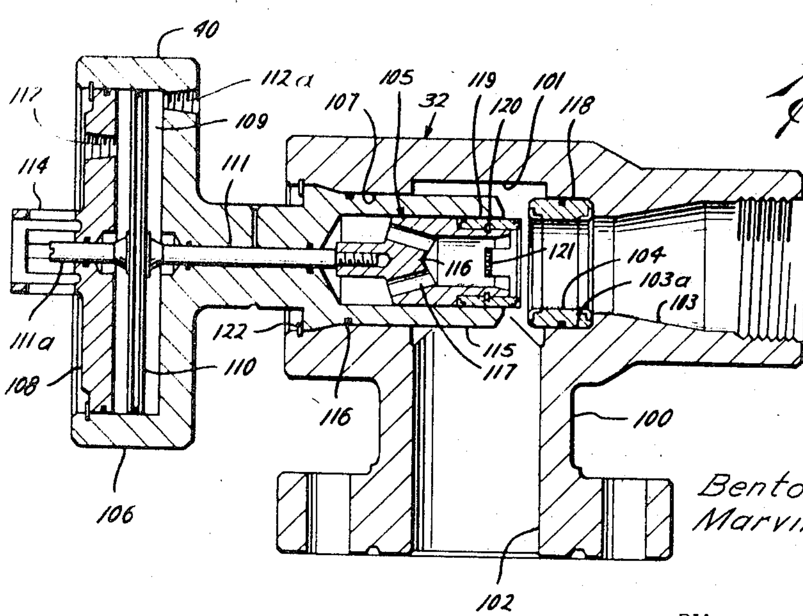


Fig. 5



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3,429,385

APPARATUS FOR CONTROLLING THE PRESSURE IN A WELL

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Int. Cl. E21b *3/12, 21/00, 47/06*

ABSTRACT OF THE DISCLOSURE

A choke is connected to an outlet from the upper end of the annulus between a well bore penetrating an earth formation containing fluid under pressure and a drill string extending into the well bore. When a kick is encountered during drilling of the well, a blowout preventer at the wellhead about the outlet may be closed to divert drilling fluid circulating through the drill string and annulus through the choke. The choke is responsive to a bias and a control signal for regulating the pressure of the drilling fluid in order to maintain the differential between the bottom hole pressure of such drilling fluid and the pressure of the formation fluid at a predetermined value. Means are provided for producing a control signal and a bias which cooperate to cause the choke to respectively increase or decrease the formation fluid pressure within the outlet automatically in response to a deviation, negative or positive, from said predetermined pressure differential, whereby the outlet pressure approaches a value at which such deviation is zero. The bias is a signal representing the pressure of the drilling fluid within a standpipe connected to the upper end of the drill string, and the control signal represents the sum of the circulating pressure loss within the drill string, the static pressure of the drilling fluid in such standpipe, and the predetermined pressure differential. The signal producing means includes a means for sensing the product of the density and the square of the rate of circulation of drilling fluid within the upper end of the drill string, which is useful in computing the circulating pressure loss within such string.

This invention relates to the control of the pressure of fluid within the annulus between a well bore and 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 systems in which the well is controlled by means of a desired 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 use in such systems and methods.

In systems of this type, it is the usual practice 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 this back pressure in the 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 well bore—i.e., prevent them from flowing into the well bore. 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. More particularly, the choke is preferably adjustable so that, in controlling the well pressure, it may be so regulated as 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 these systems, as distinguished from systems employing conventional positive chokes, an effort is made to so regulate the choke as to maintain a constant bottom-hole pressure without having to change the circulating rate.

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In the use of one such system, when a "kick" is encountered, and with the preventer closed, the mud pumps are stopped, the choke is closed, and shut-in pressure is observed at the manifold upstream of the choke. The pump is then started slowly and 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. This maintenance of a constant pressure in the standpipe continues until the "kick" is circulated out of the annulus.

The user then calculates the mud weight increase necessary to contain the formation fluid, and begins to pump the heavier mud into the drill string while now adjusting the choke 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. This, of course, is the drill string during both circulation of the "kick" out of the annulus and circulation of heavier mud up the annulus, and the annulus when heavier mud is circulated down the drill string.

An object of this invention is to provide a system of this general type 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.

Another object is to provide equipment for such a system which automatically senses certain conditions in the well in such a manner as to enable the circulating rate to vary in the use of the system, and also to permit the construction and operation of other equipment for the system to be greatly simplified.

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

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

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

FIG. 3 is a diagrammatic illustration of a pneumatic system within the console of FIG. 2;

FIG. 4 is a diagrammatic illustration of a portion of the pneumatic system of FIG. 3, with a switch thereon moved to an alternate position;

FIG. 5 is an enlarged cross sectional view of a choke in the control system;

FIG. 6 is an enlarged longitudinal cross sectional view of a sensing device in the control system; and

FIG. 7 is another longitudinal sectional view of the sensing device, as seen along broken line 7—7 of FIG. 6.

With reference now to the details of the above-described drawings, the drilling control system illustrated in FIG. 1 is installed upon a well including a casing **20** lining a portion of a well bore **21** and a casing head **22** connected to the upper end of casing **20**. A blowout preventer **23** connected above the casing head **22** has a bore **24** therethrough aligned with the bore in the casing head and rams **25** mounted therein for reciprocation between extended positions for closing the bore **24** and retracted positions for opening same. More particularly, as well known in the art, the rams are so formed on their inner ends as to seal about a drill string **26** extending through the preventer and into the well bore **21**, and thus close

It is also the practice to drill a well under pressure, in which case a rotating type of blowout preventer is maintained closed about the drill string during at least a portion of the drilling of the well. In this case, of course, as in the case of shutting in the well upon entry of formation fluid, the drilling mud within the annulus would be

When the signal from this sensed product is entered into the computing means, along with the depth of the well and the proper calibration factor, such computing means is automatically operable to compute the circulating pressure loss in accordance with the formula:

$$dP=KMV^2D$$

wherein

dP=Circulating pressure loss
K=calibration factor
M=mud density
V=mud circulation rate
D=depth of the well.

This computed circulating pressure loss, is as previously noted, indicated on the dial **60** on the control panel of the console **50**.

It may be possible, in the use of this system, to ignore the effect of a change in well depth upon the circulating pressure loss. In this case, well depth need not be measured and entered into the computing means of the console. Thus, circulating pressure loss is calculated in accordance with the formula:

$$dP=KMV^2$$

wherein

dP=circulating pressure loss
K=calibration factor
M=mud density
V=mud circulation rate

As illustrated diagrammatically in FIG. 1, the choke **32** includes a flow-restricting member which is urged toward (to the right) and away from (to the left) maximum flow-restricting position by means of an operator **40**. As will be described more fully hereinafter in connection with FIG. 5, the operator includes a piston sealably slidable within a cylinder and connected by a stem to the flow-restricting member. Thus, fluid pressure on the left-hand side of the operator piston urges the member toward maximum flow-restricting position, while fluid pressure on the opposite right-hand side thereof urges such member away from maximum flow-restricting position. For reasons to be described to follow, in this embodiment of the choke there are equal pressure responsive areas on opposite sides of the operator piston.

The opposite sides of the operator **40** for the choke **32** are connected with fluid lines **65** and **66** leading to the console. More particularly, a signal transmitted from the computing means through the fluid line **65** urges the flow-restricting member of the choke **32** to the right and thus toward maximum flow-restricting position. On the other hand, a signal transmitted from the computing means through the fluid line **66**, acts upon the right-hand side of the operator **40** so as to urge the flow-restricting member to the left and away from maximum flow-restricting position. These two signals bear the same ratio to the pressure values they represent.

As will be described to follow, the user switches the system between standpipe and manifold control, by merely manipulating a lever **67** on the control panel. More particularly, the user is able to swing the lever between an "up" position to place the system on standpipe control, as during circulation of the "kick" out of the annulus and circulation of heavier mud upwardly within the annulus, and a "down" position to place the system on manifold control, as during circulation of the heavier mud down to the bottom of the hole. Thus, the user merely manipulates the lever from one position to another at the proper stage in the control of the well.

The console **50** also has a means for producing and entering into the computer a signal which is a mathmetical function of the sum of the static condition of the standpipe pressure and a selected pressure which represents a desired safety margin. This includes a knob **68***a* adjacent a dial **68** on the control panel for indicating such sum. This

static pressure is observed by the user upon stopping the mud pumps and closing the blowout preventer rams about the drill string. The sum of static pressure and the selected pressure indicated on the panel and the signal entered into the computing means, which automatically adds such signal to the signal which is a mathematical function of the computed circulating pressure drop and transmits a signal proportional to their sum through the line **65** to the left-hand side of the choke operator **40** as the "kick" is circulated out of the annulus.

The console **50** also includes a secondary computing means for determining the increase in mud weight necessary to contain the well formation and for indicating it on the dial **99** on the front panel of the console in pounds per gallon. More particularly, this secondary computing means is integrated with the primary computer in that it receives and properly combines the values entered into the primary computer for static pressure, as indicated on dial **68**, and depth of the well, as indicated by dial **58**.

As shown in FIG. 3, line **51***a* connects standpipe transmitter **51** with the gauge having dial **52**, and line **55***a* connects the manifold transmitter **55** with the gauge having dial **56**. As also shown in FIG. 3, the transmitter lines **51***a* and **55***a* continue beyond the gauges for connection with switch means in the form of a valve body **70** having a valve member **71** with passageways therein switchable by means of the lever **67** between the alternate positions on FIG. 3 and FIG. 4. In the position of FIG. 3, one end of the left-hand passageway connects with the line **51***a* from transmitter **51**, while in the position shown in FIG. 4, such passageway connects with the line **55***a*. The opposite end of the left-hand passageway of valve member **71** remains connected with a fluid line **72** connecting with amplifier **73** for transmitting an amplified signal from line **72** to line **66** leading to the operator **40** of the choke for urging the flow-restricting member in the choke to the left and away from maximum flow-restricting position. Thus, switching of the lever **67** between its alternate positions transmits signals to the right side of the choke operator **40** proportional to standpipe pressure or manifold pressure, as desired.

As also shown in FIG. 3, a fluid line **75** connecting with the indicator **58** for the depth of the well leads to a force bridge **76** for transmitting a signal thereto which is a mathematical function of such depth. Another fluid line **77** connecting with the indicator **59** for the calibration factor also leads to the force bridge **76** for transmitting a signal thereto which is a mathematical function of such calibration factor. More particularly, these fluid lines are connected with regulators **91** and **92** which are connected with a branch **54***a* of supply fluid line **54** for transmitting signals in a desired range. This branch supply line also connects with the bridge through line **76***a*. In the force bridge, the two signals are multiplied by one another, and the product is transmitted through fluid line **78** to a second force bridge **79**.

The fluid line **63** connecting with the transmitter **62** on sensing device **61** also leads to the force bridge **79** so as to transmit thereto a signal which is a mathematical function of the sensed product of mud density times the square of the mud circulating rate. Supply fluid is also entered into the bridge **79** through line **79***a* connecting with branch supply line **54***a*, and, in this bridge, the two signals transmitted through lines **78** and **63** are multiplied by one another. The product, a signal which is a mathematical function of the circulating pressure loss, according to the above-mentioned formula, is transmitted through fluid line **80** to the dial **60** for indicating such loss.

A branch **80***a* of the fluid line **80** leads to a relay **81** to transmit thereto the signal which is a mathematical function of the circulating pressure loss. A signal which is a mathematical function of the static pressure indicated on dial **68** is also transmitted to the relay **81** by means of fluid lines **82** and **82***a* leading from such indicator. A line **68***a* also connects line **82** with a regulator **90** which, like regulators **91** and **92**, is connected to branch supply line **54***a*. In the relay **81**, the signals are added, a constant is subtracted from the sum, and the resulting signal is transmitted through fluid line **83** leading to the valve casing **70**. The fluid line **82** connecting with static pressure indicator **68** also connects with the valve casing **70** to one side of the connection therewith of fluid line **83**.

Thus, upon switching of the valve member **71** by means of lever **67**, the right-hand passageway may be switched between a position connecting it with the line **82** and a position connecting it with the line **83**. The opposite end of the right-hand passageway is fixed for connection to a line **84** leading to an amplifier **85**. The outlet from the amplifier connects with line **65** leading to the left side of the choke operator **40** for transmitting a signal thereto which urges the flow-restricting member toward maximum flow-restricting position.

Thus, with the valve in the position shown in FIG. 3, the signal transmitted through line **83** connected to lines **84** and **65** to the left side of the operator **40** is proportional to the sum of circulating pressure loss, as computed and indicated upon dial **60**, and the previously measured static pressure in the standpipe plus the selected pressure, as indicated upon the dial **68**. This signal may be termed a "control signal." At the same time, and as previously mentioned, a signal is transmitted through the line **51***a* connected to lines **72** and **65** to urge the flow-restricting member away from maximum flow-restricting position with a signal proportional to standpipe pressure. This signal may be termed a "bias." However, upon switching of the valve member **71** to the position of FIG. 4, the signal transmitted through lines **84** and **66** originates from line **82**, and is thus proportional to static pressure, while the signal transmitted through lines **72** and **66** originates from line **55***a*, and is thus proportional to manifold pressure. Both the standpipe and manifold transmitters are connected to supply line **54** by means of branch line **54***b*.

As will be understood to those skilled in the art, the above-mentioned safety margin or selected pressure represents a predetermined differential between the pressure of the formation fluid and the pressure of the well fluid opposite the formation fluid. This pressure differential is a mathematical function of the standpipe pressure, the static pressure, and the circulating pressure loss in accordance with the equation:

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

wherein

P_D is the pressure differential,
P_i is the standpipe pressure,
P_s is the static pressure, and
P_l is the circulating pressure loss.

Upon entering the console **50**, fluid supply line **54** connects with a dryer **86***a*, a filter **86***b* and a pressure regulator **87**, all in series, and then continues for connection with both of the amplifiers **73** and **85**. Also, there are regulators **88** and **89** in each of the branch lines **54***a* and **54***b*. As previously noted, branch line **54***a* leads to the force bridges **76** and **79**, adding relay **81**, line **64** connecting with the transmitter **62**, for sensing element **61** and regulators **90**, **91** and **92** connecting, respectively, with the indicators for static pressure, well depth, and the calibration factor. The other branch line **54***b* is connected with each of lines **57** and **63** leading to the flowline and standpipe transmitters, respectively.

The secondary computer for determining the mud weight necessary to balance or under or over balance by a predetermined pressure the formation pressure comprises a force bridge **95** adapted to divide the static pressure times a constant by the depth of the well. For this purpose, the line **75** leading from the indicator **58** for well depth has a branch line **75***a* connecting with the bridge **95** for transmitting a signal thereto proportional to such depth.

Also, the line **82**, which transmits a signal from indicator **68** proportional to static pressure, has a branch **82***b* leading to relay **96**, which adds a constant to this signal. The sum is then transmitted as a signal from relay **96** and through line **97** to the bridge **95**. Control pressure from branch **54***a* is also connected to each of the bridge **95** and relay **96**.

The above-described signals alternately transmitted through line **65** to the left-hand side of operator **40** bear the same ratio to the indicated pressures on the control panel and, as previously mentioned, bear a fixed ratio to the ratio of the signals from transmitters **51** and **55** transmitted through line **66** to the right side of the operator to the actual pressure within the conduits on which they are mounted. More particularly, with a choke operator **40** having equal pressure responsive areas on its opposite sides, the pressure signals transmitted through lines **65** and **66**, respectively, bear the same ratio to the actual values of the measured, set or computed pressures they represent.

Thus, for example, in this system, fluid may be supplied from a suitable source through line **54** at 80–160 p.s.i. and then reduced in the regulator **87** upstream of amplifiers **73** and **85** to 70 p.s.i. Regulator **88** reduces the regulated supplied fluid in branch **54***a* from 70 p.s.i. to 20 p.s.i., and regulator **89** reduces it in line **54***b*, which connect with lines **53** and **57**, from 70 p.s.i. to 40 p.s.i.

As well known in the art, most pneumatic computer components, such as the force bridges **76**, **79** and **95** above-described, operate within a range of 3–15 p.s.i. Thus, in this system, the signals to be entered into the computers are in the same range. That is, each of the dials **58** indicating the depth of the well in feet, **59** indicating the calibration factor, and **69** indicating the sensed product of mud density times the square of its circulating rate is adapted to transmit a signal of 3 p.s.i. at its minimum reading and a signal of 15 p.s.i. at its maximum reading. Also, the dial **60** is adapted to indicate minimum to maximum values for measured circulating pressure loss in response to signals from the computer **79** in the same operating range.

The dial **68** for indicating observed static pressure is, on the other hand, adapted to transmit signals in the range of 0–15 p.s.i. However, in the relay **96**, 3 p.s.i. is added to the signal proportional to static pressure, and a signal proportional to the sum and in the range of 3–18 p.s.i. is entered into force bridge **95**. The mud weight increase computed in force bridge **95** is indicated on dial **99** on a scale corresponding to the 3–15 p.s.i. range.

In the relay **81**, on the other hand, this increment of 3 p.s.i. is taken from the signal related to the sum of computed circulating pressure loss and standpipe pressure. The adjusted signal, which is transmitted through line **83** to the switching valve, is in the range of 0–20 p.s.i., and the scales on the dials **60** and **68** for circulating pressure loss and static pressure, respectively, range from 0–4,000 p.s.i. and 0–5,000 p.s.i. Thus, the signal transmitted through line **83** bears the same ratio to the sum of the values indicated on these scales as does the signal transmitted through line **82** to the value shown on the static pressure scale until the sum reaches 20 p.s.i. as supplied to the relay. More particularly, the signal in line **72** is doubled in amplifier **73**, while the signal in line **84** is quadrupled in amplifier **85**, so that the resulting signals on opposite sides of the choke operator are, as previously mentioned, in the same ratio to the actual pressure values which they represent.

In preparing to control the well with this system, and while drilling with the well open, the user will, from time to time, adjust the knob **58***a* for correcting the depth of well to be entered in the computer. The mud density and circulating rate need not be changed or adjusted since their product, in the above-mentioned formula, is automatically sensed and entered into the computer continuously during circulation of the mud. Thus, after adjusting the depth of the well setting on dial **58**, the user need only compare the standpipe pressure indicated on dial **52** with the circulating pressure loss indicated on dial **60**. If they are not in agreement, the user adjusts the knob **59***a* so as to change the calibrating factor in order to bring the circulating pressure loss into agreement with the standpipe pressure. When this is done, the user records the adjusted calibration factor which is now entered into the computer. Alternatively, and as previously described, the change in well depth may be ignored.

The user further prepares for the "kick" by moving the lever **67** up to standpipe control, which in turn moves valve member **71** to the right to the position of FIG. 3. Then, 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 blowout preventer rams **25** about the drill string **26**. After a short wait, he then reads the standpipe pressure on the dial **52** and the manifold pressure on the dial **56** and records both of them. He then sets the dial **68** by means of knob **68***a* to indicate the static standpipe pressure which he has read on dial **52** plus any desired safety margin for overbalance, and starts the mud pumps.

As will be apparent from the foregoing description, the force bridges **76** and **79** automatically computes and produces the signal which is a mathematical function of the circulating pressure loss, and the relay **81** automatically adds this signal to the signal proportional to the setting on dial **68** and substracts 3 p.s.i. from the sum to produce a signal which is proportional to the sum of the pressure values represented. This latter signal is then transmitted through the line **83** to the switch means including the valve casing **70** and switchable valve member **71**. With the valve member moved to the right, as shown in FIG. 3, this signal is transmitted through lines **84** and **65** to the choke operator **40** for urging the flow-restricting member toward maximum flow-restricting position. At the same time, a signal proportional to the standpipe pressure is transmitted through line **51***a*, through valve **70**, into line **72** and then through line **66** to choke operator **40** for urging the flow-restricting member away from maximum flowline-restricting position. Thus, the well is controlled through the drill string by maintaining a bottom hole pressure equal to the sum of the hydrostatic head of the mud and the sum of static standpipe pressure and the selected pressure, plus that part of circulating pressure loss occurring in the annulus. The circulating pressure loss is constantly being computed, and automatically compensates for changes in the mud circulating rate.

As drilling mud is circulated through the well, the choke **32** will automatically adjust for any deviation from the predetermined pressure differential so as to maintain the standpipe pressure at the level required for maintaining the bottom hole pressure substantially constant.

When the "kick" has been circulated out of the well bore, level **67** is moved to its lower, manifold control position, and the heavier mud is circulated down through the 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 a dial **99** on the console **50**.

Movement of the lever **67** switches the valve member **71** to the left-hand position shown in FIG. 4. In this shifted position of the valve member, a signal proportional to manifold pressure is transmitted by line **55***a* through the switch to line **72** and thus into the line **66**. Thus, this signal is transmitted to the choke operator **40** for urging the flow-restricting member away from maximum flow-restricting position. At the same time, a signal proportional to the static pressure which was set on the dial **68** is transmitted through line **82** and the switching valve into line **84** where it is transmitted by amplifier **85** and through line **65** to the operator **40** of the choke. This latter signal urges the flow-restricting member toward maximum flow-restricting position. Since it is a mathematical function of the set static pressure, this signal is a constant so that the flow-restricting member of the choke **32** automatically adjusts in such a manner that the opposing signal through line **66**, which is proportional to the manifold 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 **68***a* to change the reading on the static pressure dial **68** to zero, and moves the lever **67** to the upper position of FIG. 2 for switching the system to drill string control. This, of course, switches the valve member **71** back to the right, as shown in FIG. 3. However, since the dial **68** for static pressure has been moved to zero, the sum which is transmitted from the relay **81** to the valve **70** by means of line **83** is proportional only to the circulating pressure loss, so that the signal transmitted to the operator **40** for urging the flow-restricting member to flow-restricting position is similarly a signal proportional only to the circulating pressure loss. This signal, of course, is opposed by a signal proportional to standpipe pressure transmitted through line **51***a* and the switching valve into line **72** to the operator **40** through line **66**. Thus, during circulation of the heavier mud upwardly through the annulus of the well, the choke automatically adjusts to maintain the standpipe pressure at a level equal to the computed circulating pressure. The user begins to weigh the mud returns as soon as the manifold pressure indicated on dial **56** 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 reduces 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 counters 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, the reads and sets the static pressure in the standpipe upon the dial **68** after the well has been shut in for a short time. Normally, he will add to this reading an overbalance and set the sum on the dial **68**. He further reads and records the choke manifold and standpipe pressures, as indicated on dial **56**, moves the lever **67** to standpipe control position, and resumes mud circulation.

In this method, the user immediately begins to circulate the mud into the drill string at whatever rate he is able to mix the mud. He reads the dial **99** indicating mud weight increase 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.

More particularly, as the heavier mud reaches the sensing device **61**, the user observes the change in circulating pressure loss reflected on the dial **60**, and reduces the static pressure reading on the dial **68** a corresponding amount by suitable adjustment of the knob **68***a*. 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 manifold pressure dial **56**, 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.

As shown in FIG. 5, in its preferred form, the choke **32** includes a body **100** having a chamber **101** therein intersected by an inlet **102** to the chamber and an outlet **103** 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 **103** with the chamber **101** forms an annular seat **104** which is adapted to be substantially closed by an annular, flow-restricting member **105** which moves axially toward and away from the outlet. Thus, in the position of the flow-restricting member shown in FIG. 5, there is an annular opening between the inner end of the flow-restricting member and the inner end of the seat **104** through which fluid may pass from the inlet **102** to the outlet **103**. As the member **105** 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 **105** moves to the right, it further restricts the annular opening between its inner end and the inner end of seat **104**, so as to thereby increase the back pressure in the annulus **29**. In its extreme right-hand position, the inner end of member **105** moves a short distance into the inner end of the seat **104** so as to restrict flow through the choke to a maximum extent.

The operator **40** comprises a T-shaped fitting **106** having its small end removably mounted within an opening **107** in choke **100** to close same. This opening extends from the chamber to the outer end of the body in axial alignment with both the outlet **103** and the seat **104**, and thus parallel to the direction of movement of member **105**. Thus, in a manner to be described hereafter, the member **105** is guidably slidable within the small end of fitting **106**.

The opposite large end of the fitting **106** comprises a cylinder **109** formed between a cup-shaped opening covered by a plate **108** releasably secured to and sealably engaged with the inside of the cup. A piston **110** is sealably slidable within the cylinder for reciprocation along the axis of reciprocation of the member **105**, and a stem **111** extends through the fitting to connect the piston to a head on the flow-restricting member **105**. Thus, reciprocation of the piston **110** of the operator will cause a corresponding reciprocation of the flow-restricting member **105** 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 each of the systems. Thus, there is a threaded port **112** in the plate **108** for connection with the line **65**. Also, there is a port **112*a*** through the cup for threaded connection with the line **66**.

The stem **111** has a telltale **111*a*** extending sealably through the plate **108** and of the same diameter as the portion thereof extending sealably through the fitting to connect piston **110** to flow-restricting member **105**. Thus, the piston **110** is balanced in this preferred embodiment of the choke **32**, which is of advantage in responding to the signals. The telltale **111*a*** is visible through a slotted guard **114** mounted about it on the outer side of plate **108** to permit the 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 opening **107** and is sealed with respect thereto by a seal ring **116**. This end of the fitting is hollow to provide a skirt **115** which extends inwardly beyond opening **107** and into the chamber **101** to a position close to the seat so as to support substantially the entire length of the flow-restricting member **105** which, as previously noted, fits closely within the inner diameter of the skirt **115** so as to be guided thereby during its reciprocation.

As can be seen from FIG. 5, the flow-restricting member **105** is hollow at its inner end opposite the passageway **101**, and has a head **116** on its outer end for threaded connection to the end of the stem **111** of the operator. There are a series of ports **117** extending through the head of the member **105** to freely connect the hollow interior of the member **105**, and thus the chamber **101**, with the area between the head and the closed end of the fitting at the base of the skirt **115**. In this way, pressure within the choke **32** acts only over the cross sectional area of the stem **111** to urge the flow-restricting member **105** 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 **111*a***, which, as previously mentioned, is of the same cross sectional area as the stem **111**. Thus, there is a minimum of tendency for pressure within the choke to urge the member **105** away from flow-restriction position, particularly due to pressure within outlet **103** when the member **105** is in its extreme position within seat **104**.

As can be seen from FIG. 5, the seat **104** comprises a removable ring which is cylindrical so as to be reversible end-for-end within an enlarged diameter portion **103*a*** of the outlet **103** 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 **105** into its extreme flow-restricting position. A seal ring **118** is received about a central portion of the outer diameter of the ring so as to sealably engage with the recessed portion **103*a*** in either end-for-end position of the ring.

The hollow portion of flow-restricting member **105** is recessed about its open end to receive a removable sleeve **119**, which is also cylindrical so as to be reversible end-for-end, similarly to the seat ring **104**, on the hollow portion of such member. More particularly, the sleeve **119** 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 **115**. The opposite ends of the outer diameter of the sleeve are chamfered for guiding into the oppositely facing end of the ring **104**.

A snap ring **120** is carried within the oppositely facing grooves on the inner diameter of the ring **119** and outer diameter of the recessed portion of the member **105** so as to releasably retain the sleeve about such member body. Access is had to the snap ring **120** by means of a slot **121** 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 a collapsed position to permit insertion and removal of the sleeve **119**.

The inner corners of the seat **104** and tthe outer corners of the sleeve **119** 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 **106**, including the annular skirt **115** thereof, is releasably mounted within the opening **107** of the choke body by means of snap ring **122** engaging in a groove in an outer end of opening **107**. 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 **116** is sealably engaged with such opening. As can be seen from FIG. 5, cover **108** is similarly releasably secured to the cup-shaped open end of the fitting. As can also be seen from FIG. 5, suitable seals are provided about the openings in plate **108** and the small end of the fitting **106** so as to seal about the stem **111** connecting the flow-restricting member **105**.

As will be apparent from the foregoing, upon removal of the small end of the fitting from within opening **107**, the seat ring **104** can be replaced or reversed end-for-end, therethrough. Also, of course, with the fitting removed, the sleeve **119** may also be replaced, or reversed end-for-end.

As previously described, and as shown in FIGS. 6 and 7, the sensing device **61** comprises a tubular conduit **125** 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 **126** extending diametrically through the opposite sides of the conduit for rotation therein, and an arm **127** mounted on the shaft within the conduit for rotation therewith and extension longitudinally of the conduit. There is a sensing element **128** in the shape of an airfoil or hydrofoil on the end of the arm **127** remote from the shaft **126** and occupying in a neutral position, substantially the mid portion of the conduit. More particularly, the sensing element **128** 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 **127** is of flat, narrow construction, as seen along the plane shown in FIG. 6, and of convergent tapering construction from the shaft **126** to the sensing element **128**, as seen in the plane of FIG. 7. More particularly, the end of the arm **127** which surrounds the shaft **126** includes a tear-drop portion **127*a*** extending from one side to another of the conduit, as shown in FIG. 6, and secured to the shaft **126** by means of a set screw **131**.

As shown in FIG. 6, there is also an arm **129** mounted on one outer end of the shaft **126** for rotation therewith along the outer side of the conduit **125**. The end of this exterior arm **129** remote from the shaft **126** has a head **130** thereon for engagement at its lower end with an oppositely facing part on the transmitter **62** which, as previously described, is of such construction as to transmit a signal through line **63** proportional to the force by which the flowing drilling mud urges the sensing element **128** out of its neutral position. This force is, of course, transmitted to the head **130** through the arm **127**, shaft **126**, and arm **129**.

The transmitter **62** is of a so-called null balance type which is operable to return the head **130** and thus the arm **129** to its original position with a force 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 **61**, the flowing mud acts upon the element **129** to urge it out of the neutral position shown in FIG. 7 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 **62**, which in turn transmits a signal to the above-described product to the console **50**.

As shown in FIG. 6, the opposite ends of the shaft **126** extend through openings **132** in sleeves **133** on opposite exterior sides of conduit **125**. The inner end of each opening **132** has a shoulder **134** against which a seal ring **135** is held by means of a ball bearing **136**. The bearing is in turn held tightly against the seal ring by means of a gland nut **137** threadedly engaged with the outer threaded end of opening **132**. Preferably, the seal ring **135** includes a thin disc of Teflon whose inner diameter is held tightly against the outer diameter of the shaft **126**. By means of the gland nut **137** engaging against bearing **136**, only the outer diameter of the Teflon ring is held against rotation, so that its inner diameter is free to rotate with the shaft **126** as the sensing element **128** 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 **126**, even during its small arc of rotation.

The transmitter **62** is releasably mounted upon a platform **138** suspended from the lower side of the conduit **125**, as seen in FIG. 7.

From the foregoing, it will be seen that this invention is one well adapted to attain all of the ends and objects hereinabove set forth, together with other advantages which are obvious and which are inherent to the apparatus and method.

The invention having been described, what is claimed is:

1. A system for controlling the pressure of a fluid within the annulus between a well bore penetrating a formation containing fluid under pressure and a drill string extending into the well bore, wherein drilling fluid is circulated through the drill string and the annulus, and there is a pressure differential, positive or negative, by which the bottom hole pressure of such drilling fluid exceeds the formation pressure, including a choke for connection to the upper end of the annulus, said choke having a flow-restricting member movable toward and away from maximum flow-restricting position and a signal responsive operator for so moving the flow-restricting member, means for sensing the pressure of fluid within the upper end of the drill string and for producing a first signal which is a mathematical function of the pressure so sensed, means for transmitting the first signal to the choke operator for urging the flow-restricting member away from maximum flow-restricting position, means for sensing the product of the density and the square of the rate of circulation of fluid within the upper end of the drill string and producing a signal which is a mathematical function of such product, means for producing a signal which is a mathematical function of a selected calibration factor, means for combining the two last-mentioned signals in accordance with the equation:

$$dP = KMV^2$$

wherein

dP=circulating pressure loss
K=calibration factor
M=density
V=circulation rate

and producing a second signal which is a mathematical function of the circulating pressure loss, means for producing a third signal which is a mathematical function of the sum of static pressure of fluid sensed within the upper end of the drill string and a predetermined pressure differential, means for producing a fourth signal which is a mathematical function of the sum of the second and third signals, and means for transmitting the fourth signal to the choke operator to urge the flow-restricting member toward maximum flow-restricting position and cooperating with said first signal to cause the choke to increase or decrease the pressure in the upper end of the annulus automatically in response to deviations from said predetermined pressure differential, and thereby maintain said bottom hole pressure substantially constant.

2. A system for controlling the pressure of a fluid within the annulus between a well bore penetrating a formation containing fluid under pressure and a drill string extending into the well bore, wherein drilling fluid is circulated through the drill string and the annulus, and there is a pressure differential, positive or negative, by which the bottom hole pressure of such drilling fluid exceeds the formation pressure, including a choke for connection to the upper end of the annulus, said choke having a flow-restricting member movable toward and away from maximum flow-restricting position and a sig-

nal responsive operator for so moving the flow-restricting member, means for sensing the pressure of fluid within the upper end of the drill string and for producing a first signal which is a mathematical function of the pressure so sensed, means for transmitting the first signal to the choke operator for urging the flow-restricting member away from maximum flow-restricting position, means for sensing the product of the density and the square of the rate of circulation of fluid within the upper end of the drill string and producing a signal which is a mathematical function of such product, means for producing a signal which is a mathematical function of a selected calibration factor, means for producing a signal which is a mathematical function of the depth of the well, means for combining the three last-mentioned signals in accordance with the equation:

$$dP = KMV^2$$

wherein:

dP=circulating pressure loss
K=calibration factor
M=density
V=circulation rate
D=depth of the well

and producing a second signal which is a mathematical function of the circulating pressure loss, means for producing a third signal which is a mathematical function of the sum of static pressure of fluid sensed within the upper end of the drill string and a predetermined pressure differential, means for producing a fourth signal which is a mathematical function of the sum of the second and third signals, and means for transmitting the fourth signal to the choke operator to urge the flow-restricting member toward maximum flow-restricting position and cooperating with said first signal to cause the choke to increase or decrease the pressure in the upper end of the annulus automatically in response to deviations from said predetermined pressure differential, and thereby maintain said bottom hole pressure substantially constant.

3. A system for controlling the pressure of a fluid within the annulus between a well bore penetrating a formation containing fluid under pressure and a drill string extending into the well bore, wherein drilling fluid is circulated through the drill string and the annulus, and there is a pressure differential, positive or negative, by which the bottom hole pressure of such drilling fluid exceeds the formation pressure, including a choke for connection to the upper end of the annulus, said choke having a flow-restricting member moveable toward and away from maximum flow-restricting position and a signal responsive operator for so moving the flow-restricting member, means for sensing the pressure of fluid within the upper end of the drill string and producing a first signal which is a mathematical function of the pressure so sensed, means for transmitting said first signal to the choke operator to urge said flow-restricting member away from maximum flow-restricting position, means for producing a second signal which is a mathematical function of the circulating pressure loss of fluid circulating within the well bore, means for producing a third signal which is a mathematical function of the sum of a sensed static pressure of fluid within the upper end of the drill string and a predetermined pressure differential, means for producing a fourth signal which is a mathematical function of the sum of said second and third signals, means for transmitting each of said third and fourth signals to the choke operator for urging said flow-restricting member toward maximum flow-restricting position, means for sensing the pressure of fluid within the upper end of the annulus upstream of the choke and producing a fifth signal which is a mathematical function of the pressure so sensed, means for transmitting said fifth signal to the choke operator to urge the flow-restricting member away from maximum flow-restricting position, means for interrupting the transmission of one of said first and fifth signals to the choke operator while the other is being transmitted thereto, and means for interrupting the transmission of one of said third and fourth signals to the choke operator while the other is transmitted thereto.

4. Apparatus for use as part of a pressure control system for a drilling well, wherein the system includes a choke connected to the upper end of the annulus between the well bore and a drill string extending into the well bore, and the choke has a flow-restricting member moveable toward and away from flow-restricting position and a signal responsive operator for so moving the flow-restricting member; said apparatus comprising a console having a control panel, means in the console for automatically computing the circulating pressure loss of fluid circulating within the well by combining signals which are mathematical functions of certain characteristics of the well including a selected calibration factor, the density of the fluid within the well, and the circulation rate of said fluid, means for independently entering each of said signals into said computing means, means for receiving signals which are mathematical functions of the pressure of fluid sensed within the upper end of the drill string and the upper end of the annulus, respectively, means on the control panel for indicating the computed circulating pressure loss, the entered well characteristics, and the sensed fluid pressures within the upper ends of the drill string and annulus, means on the control panel for adjusting the calibration factor, means in the console for producing a signal which is a mathematical function of the sum of a selected pressure and sensed static pressure of fluid within the upper end of the drill string, means in the console for producing a signal which is a mathematical function of the computed circulating pressure loss, means in the console for automatically adding the last two mentioned signals, and means in the console for producing a signal which is a mathematical function of the sum thereof.

5. Apparatus of the character defined in claim 4, including means for transmitting to said choke operator each of said signals which are mathematical functions of the fluid pressure sensed within the upper end of the drill string and the upper end of the annulus, respectively; said signal which is a mathematical function of the sum of selected pressure and sensed static pressure, and said signal which is a mathematical function of the sum of said last-mentioned signal and said signal which is a mathematical function of the circulating pressure loss.

6. Apparatus of the character defined in claim 5, wherein said signal transmitting means includes switch means for transmitting, in one position, the signals which are mathematical functions of the fluid sensed within the upper end of the drill string and of the sum of computed circulating pressure loss and the sum of selected pressure and sensed static pressure, and, in an alternate position, the signals which are mathematical functions of the fluid sensed within the upper end of the annulus and of the sum of selected pressure and sensed static pressure, and means for moving said switch means between said positions.

7. Apparatus for use as part of a pressure control system for a drilling well, wherein the system includes a choke connected to the upper end of the annulus between the well bore and a drill string extending into the well bore and a means for sensing and producing a signal which is a mathematical function of the product of the density and the square of the rate of circulation of a fluid within the upper end of the drill string, and the choke has a flow-restricting member movable toward and away from flow-restricting position and a signal responsive operator for so moving the flow-restricting member; said apparatus comprising a console having a control panel, means in the console for receiving said signal and automatically computing the circulating pressure loss of fluid circulating within the well by combining it with

other signals which are mathematical functions of certain characteristics of the well including a selected calibration factor, means for independently entering each of said last-mentioned signals into said computing means, means for receiving signals which are mathematical functions of the pressure of fluid sensed within the upper end of the drill string and the upper end of the annulus, respectively, means on the control panel for indicating the computed circulating pressure loss, the entered well characteristics, and the sensed fluid pressures within the upper ends of the drill string and annulus, means on the control panel for adjusting the calibration factor, means in the console for producing a signal which is a mathematical function of the sum of a selected pressure and sensed static pressure of fluid within the upper end of the drill string, means on the control panel for adjusting said last-mentioned signal and indicating said sum, and means in the console for producing additional signals which are mathematical functions of the computed circulating pressure loss and the sum of said last-mentioned signal and the signal which is a mathematical function of the sum of a selected pressure and sensed static pressure, respectively.

8. 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 control signal and a bias which cooperate to cause the choke to increase or decrease the outlet fluid 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 sensing the product of the density and the square of the rate of circulation of the drilling fluid and producing a signal corresponding to the sensed product, and means for computing a signal representing the circulating pressure loss of the drilling

fluid within the drill string by multiplying said produced signal by a signal representing each of certain well characteristics including a calibration factor.

9. Apparatus of the character described in claim **8**, wherein another well characteristic is the depth of the well.

10. For use in controlling a well, a console having a control panel, means in the console for automatically computing the circulating pressure loss of fluid circulating within the well by combining signals which are mathematical functions of certain characteristics of the well, including a selected calibration factor and the product of density of the fluid within the well and the square of the circulation rate of said fluid, means for independently entering said signals into said computing means, means for receiving signals which are mathematical functions of the pressure fluid sensed within the inlet and outlet, respectively, of the well, means on the control panel for indicating the computed circulating pressure loss, the entered well characteristics, and the sensed fluid pressures within the inlet and outlet, means on the control panel for adjusting the calibration factor, means in the console for producing a signal which is a mathematical function of the sum of a predetermined pressure differential and a sensed static pressure of the fluid within the well, and means for producing additional signals which are mathematical functions of the computed circulating pressure loss and the sum of said last-mentioned signal and the signal which is the mathematical function of the sum of the predetermined pressure differential and the sensed static pressure, respectively.

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175—38, 218; 73—151

UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,429,385 February 25, 1969

Marvin R. Jones et al.

It is certified that error appears in the above identified patent and that said Letters Patent are hereby corrected as shown below:

In the drawings, Sheet 1, Fig. 1, the reference character G should be added to show the ground level. Column 1, line 27, cancel "formation". Column 3, line 9, "spring" should read -- string --. Column 9, line 25, "computes" should read -- compute --; line 25, "produces" should read -- produce --; line 29, "substracts" should read -- subtracts --. Column 10, line 42, "counters" should read -- encounters --; line 45, "the", first occurrence, should read -- he --. Column 15, that portion of the formula reading

KMV^2 should read KMV^2D.

Column 16, line 52, after "fluid" insert -- pressure --; line 56, after "fluid" insert -- pressure --. Column 18, line 17, "pressure fluid" should read -- fluid pressure --.

Signed and sealed this 16th day of June 1970.

(SEAL)
Attest:

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