

(12) **Patent Application Publication**
Reitsma

(43) **Pub. Date:** **Oct. 25, 2007**

Publication Classification

(52) **U.S. Cl.** **175/38**; 175/57; 175/48

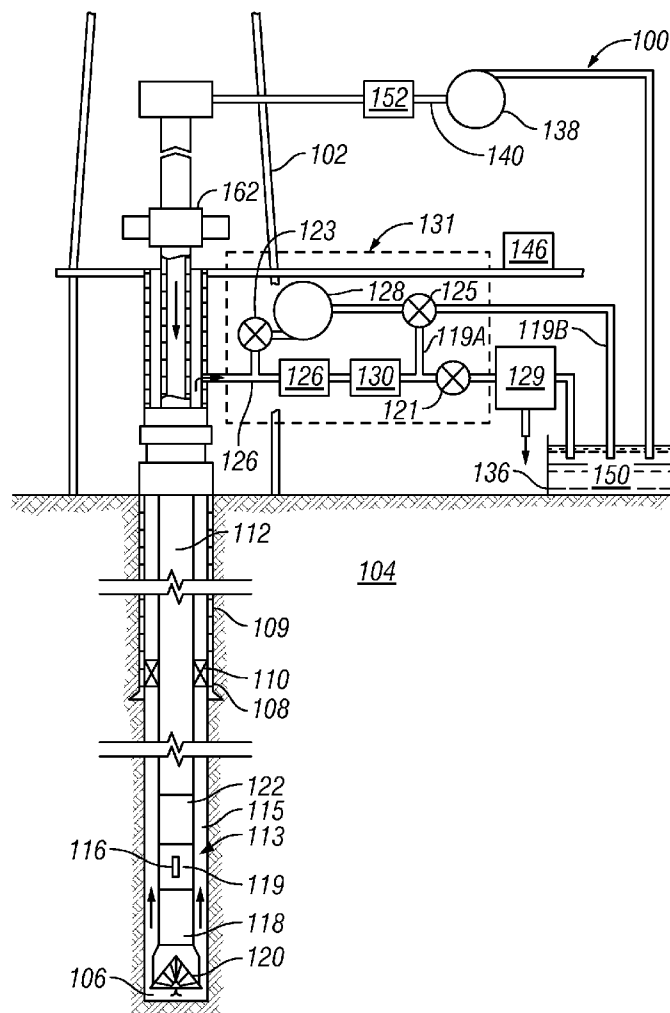
(57) **ABSTRACT**

A method for controlling formation pressure during the drilling of a borehole through a subterranean formation includes selectively pumping a drilling fluid through a drill string extended into a borehole, out a drill bit at the bottom end of the drill string, and into an annular space between drill string and the borehole. The drilling fluid is discharged to a reservoir to clean the drilling fluid for reuse. Annular space fluid pressure is selectively increased to maintain a selected fluid pressure proximate the bottom of the borehole by applying fluid pressure to the annular space. The selective increasing includes controlling an aperture of an orifice operatively coupled between the annular space and the reservoir. Fluid from the annular space is discharged other than through the orifice when the annular space fluid pressure exceeds a selected value, or drops below a selected value.

(22) Filed: **Apr. 19, 2007**

Related U.S. Application Data

(60) Provisional application No. 60/793,488, filed on Apr. 20, 2006.



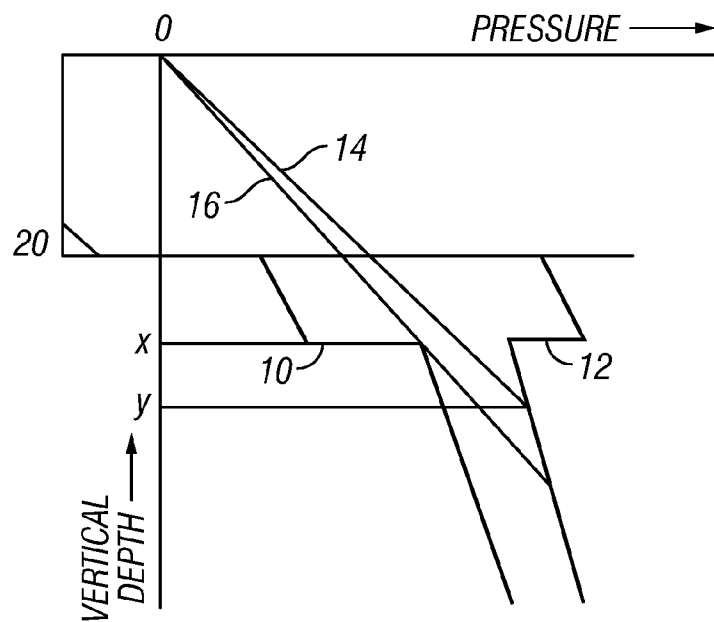


FIG. 1

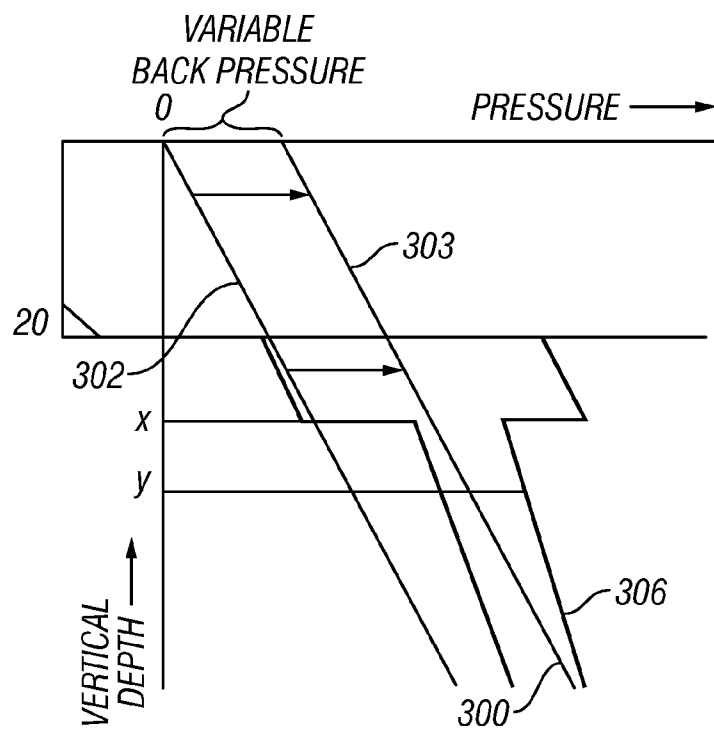


FIG. 7

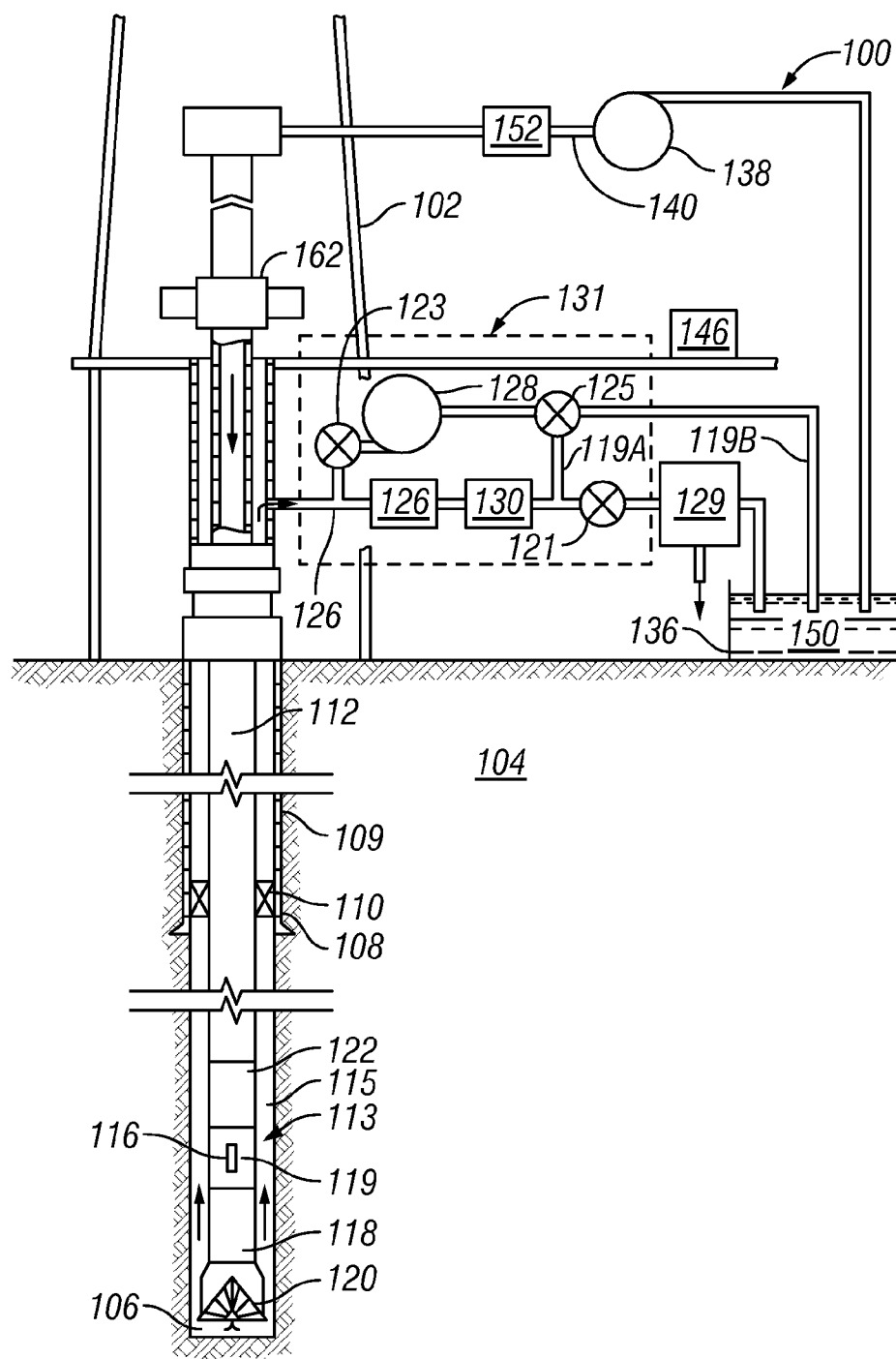


FIG. 2

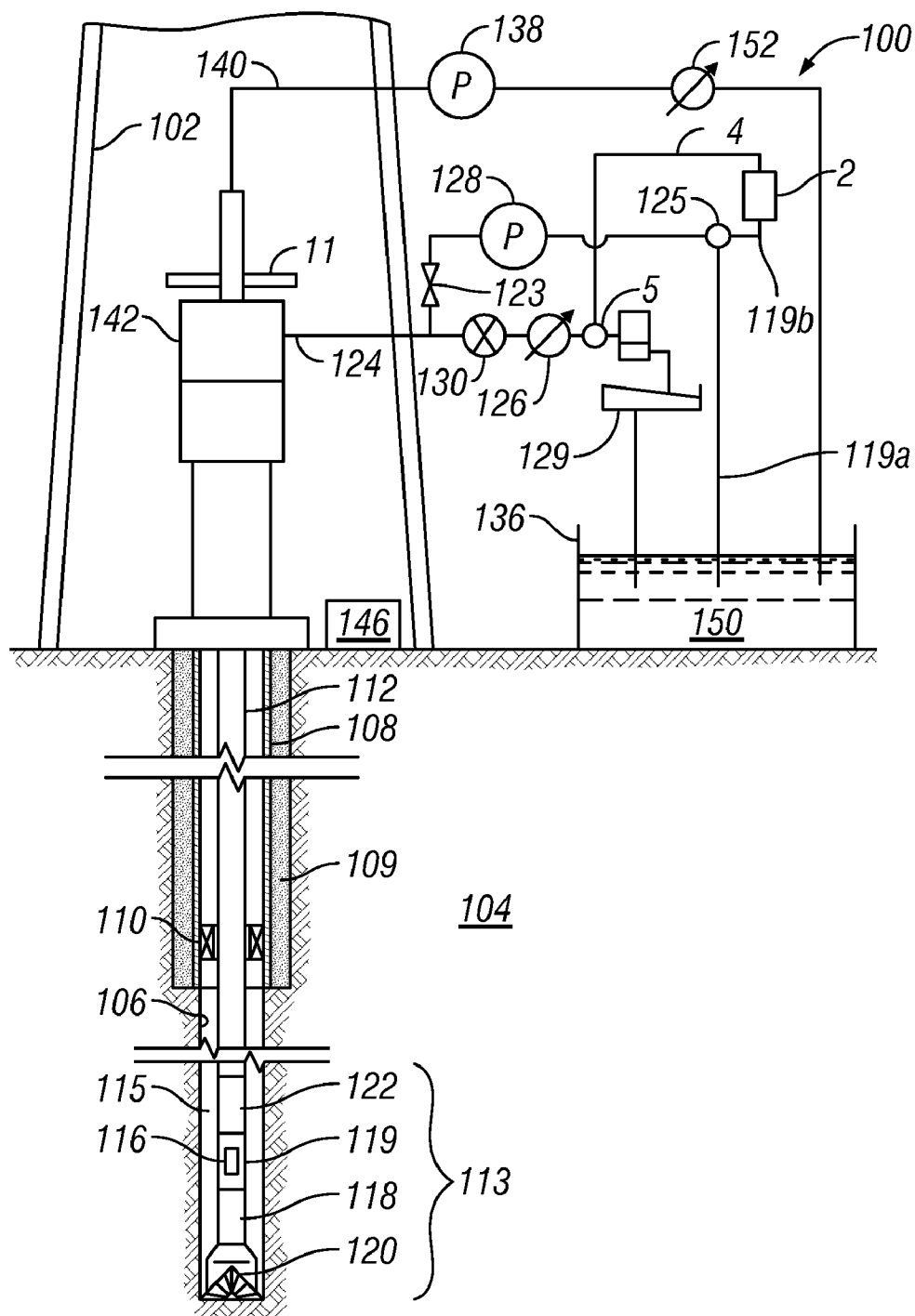


FIG. 2A

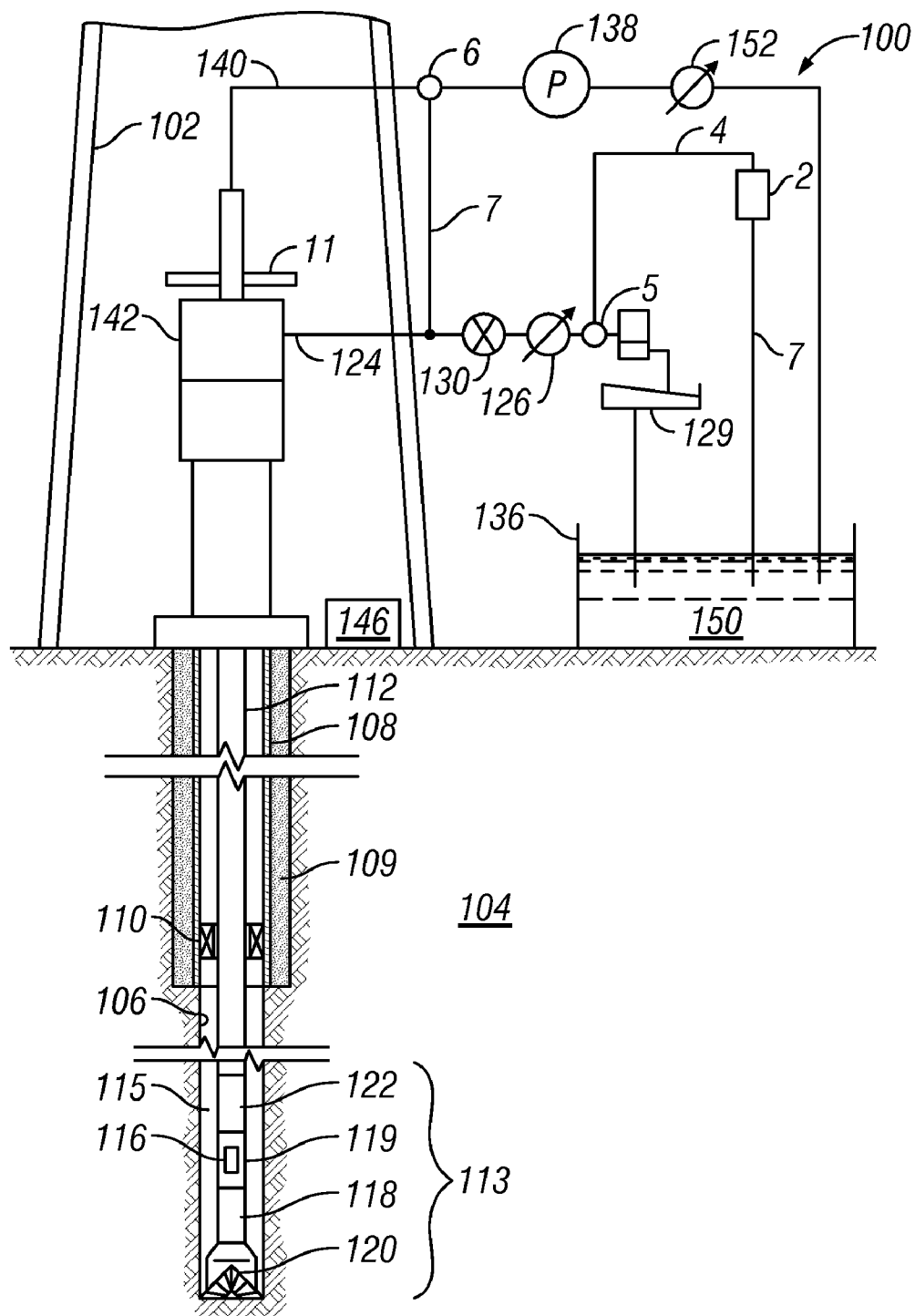


FIG. 2B

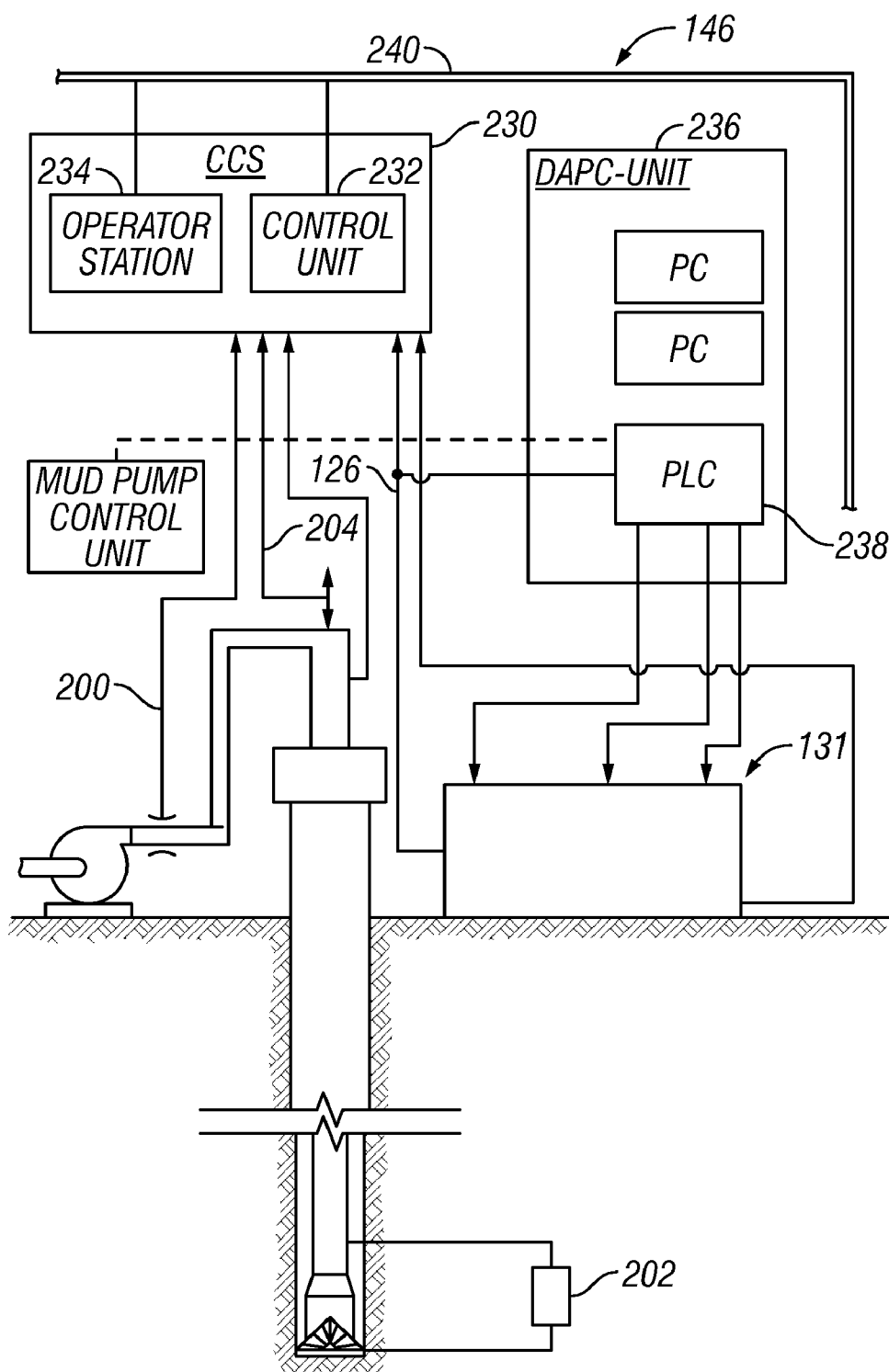


FIG. 3

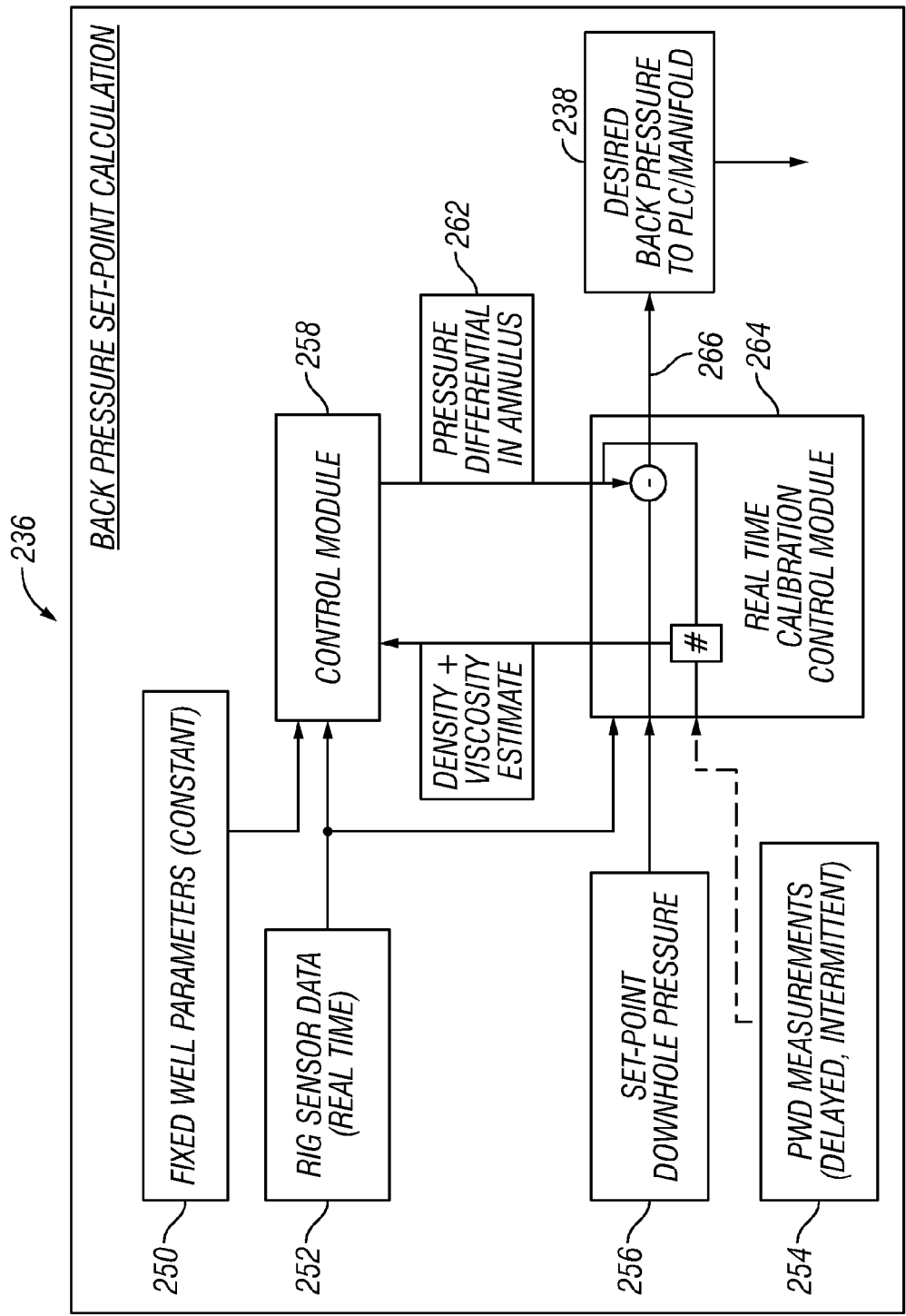


FIG. 4

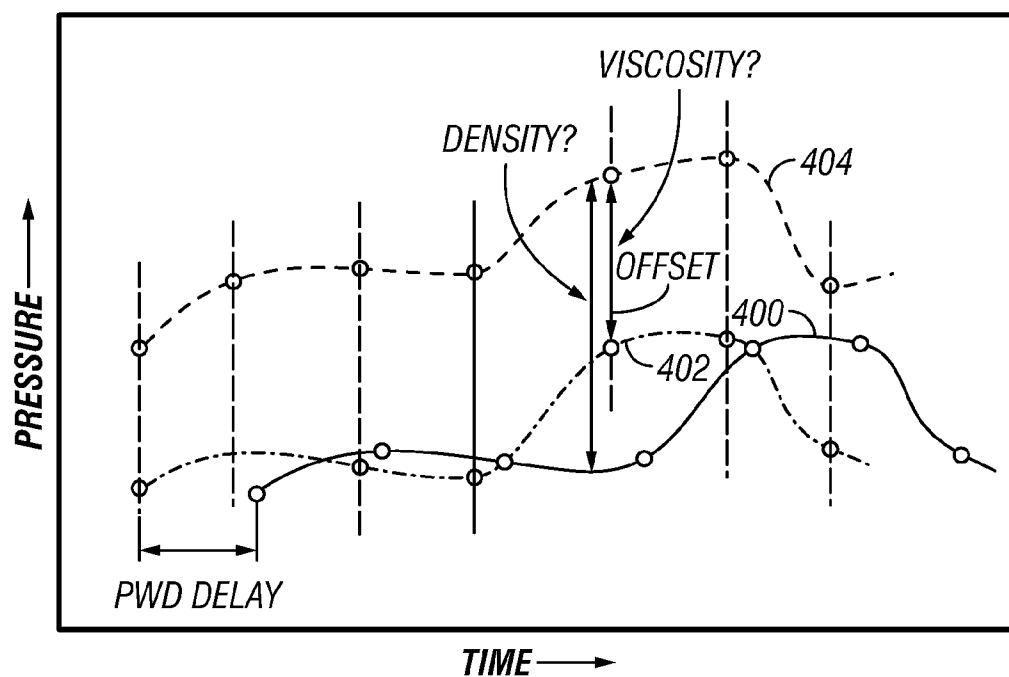


FIG. 5

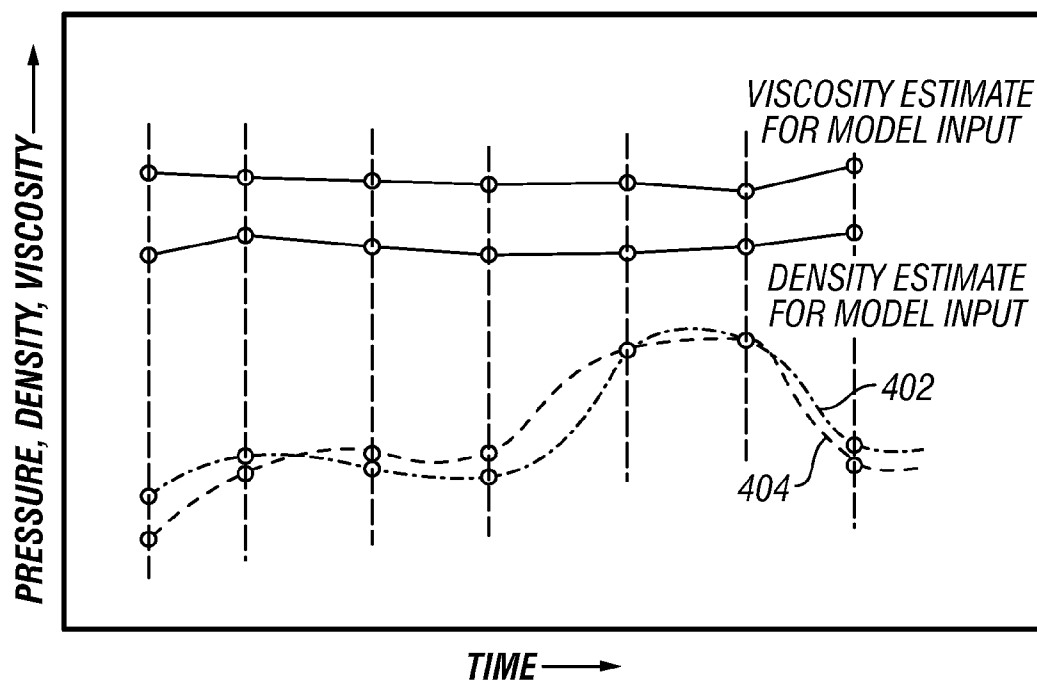


FIG. 6

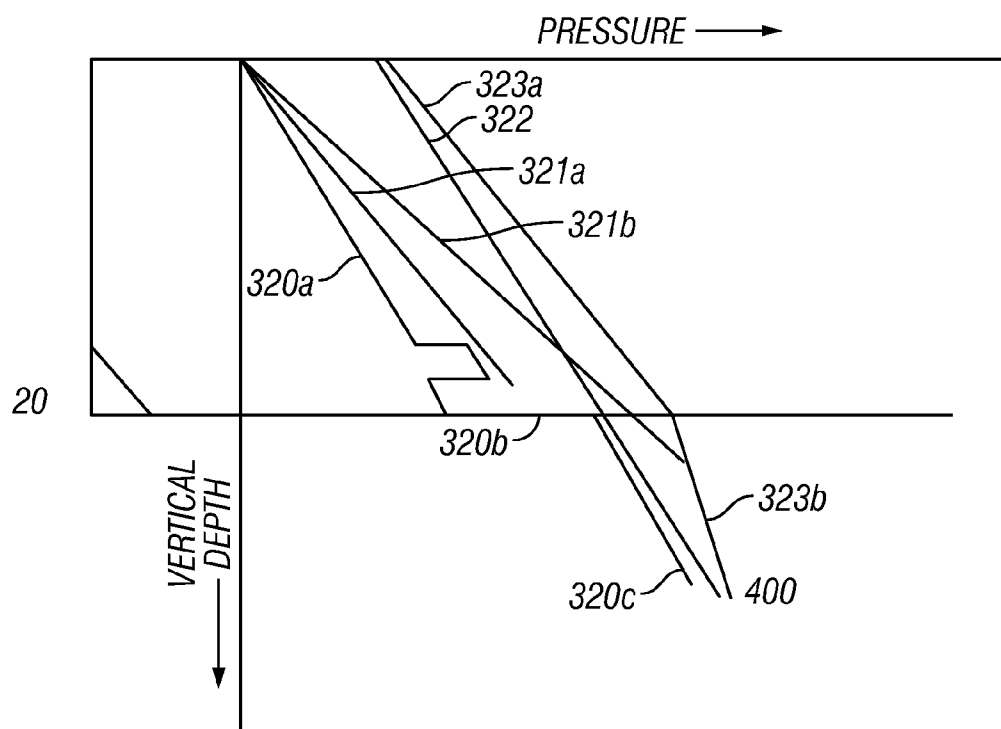


FIG. 8

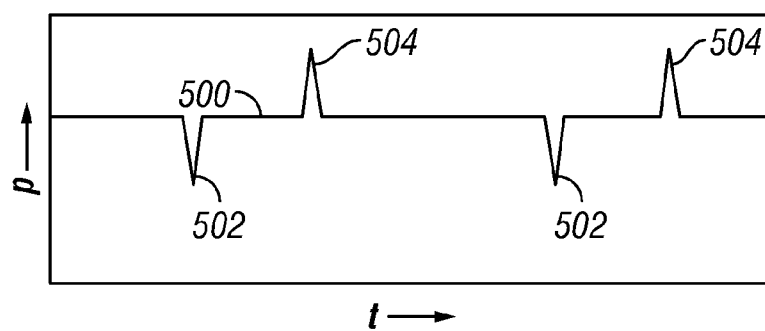


FIG. 9A

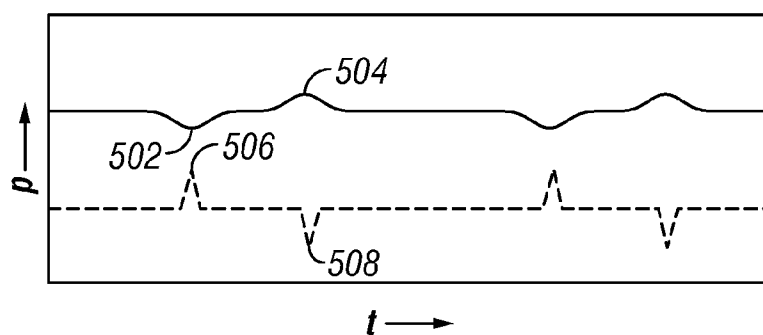


FIG. 9B

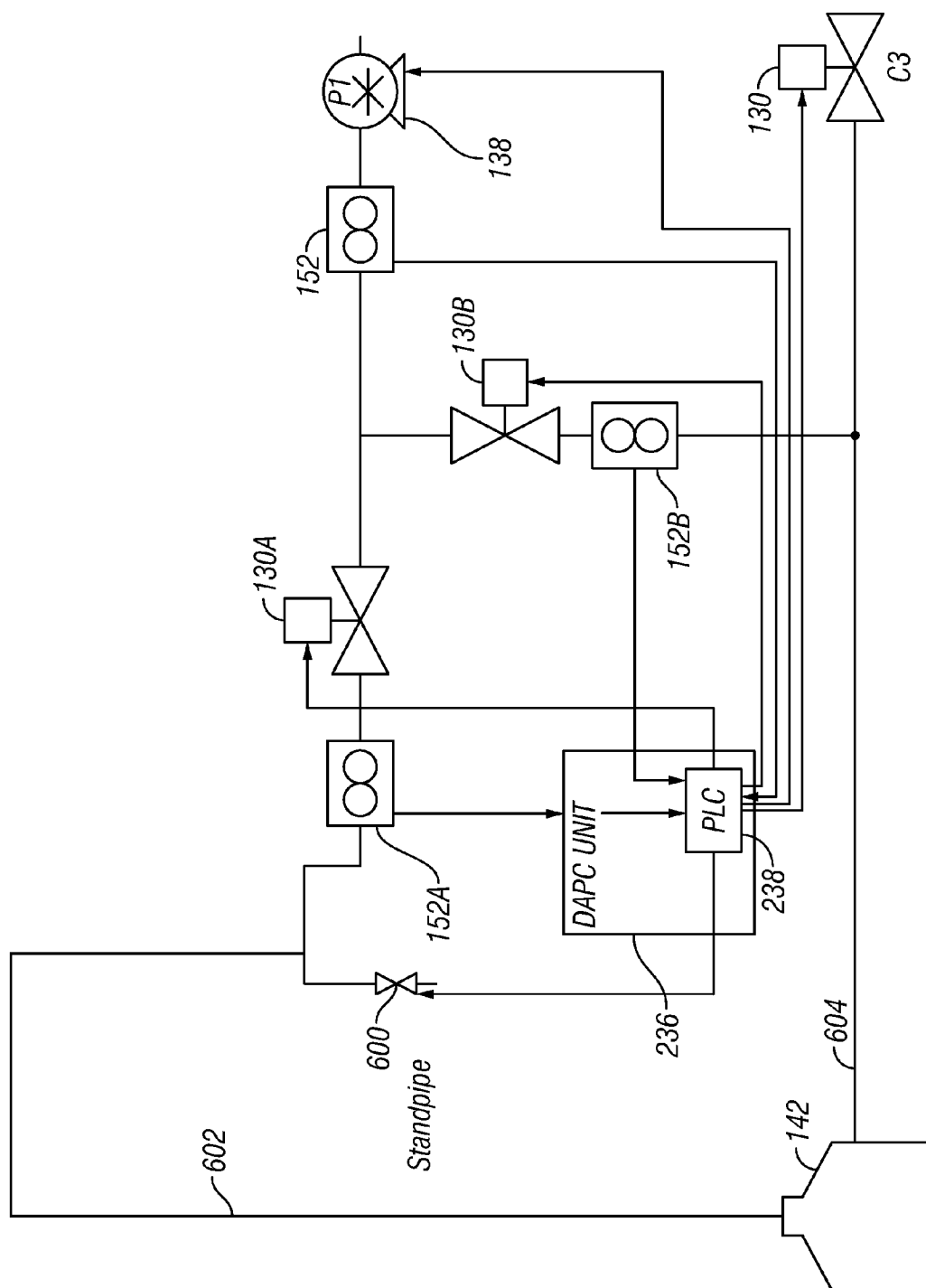


FIG. 10

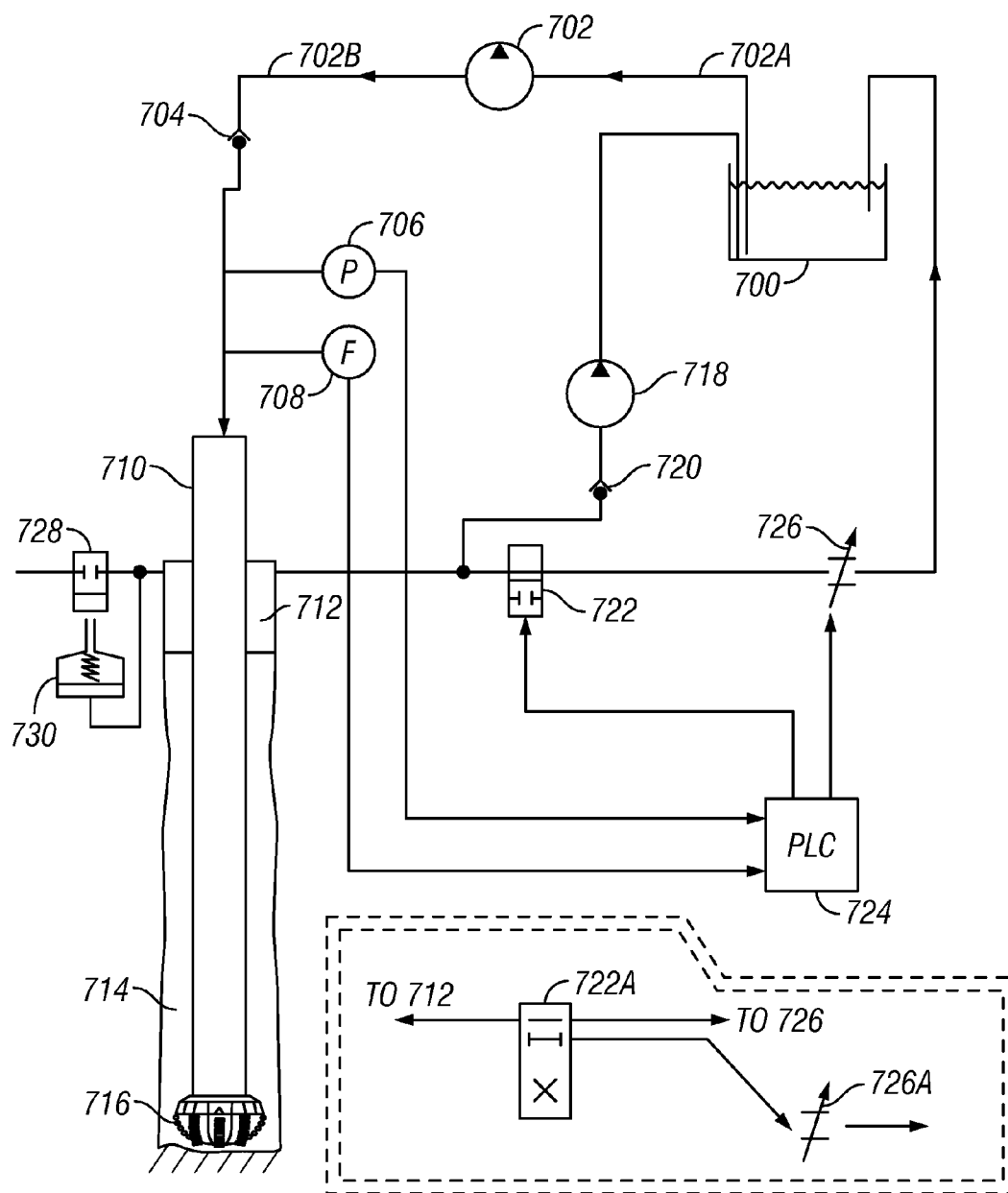


FIG. 11

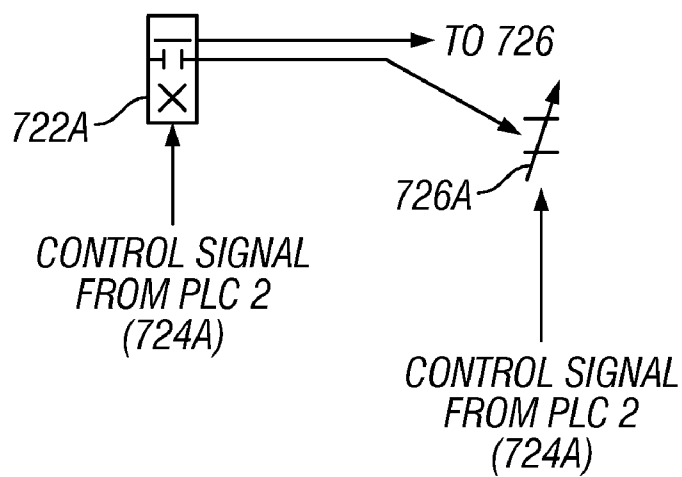
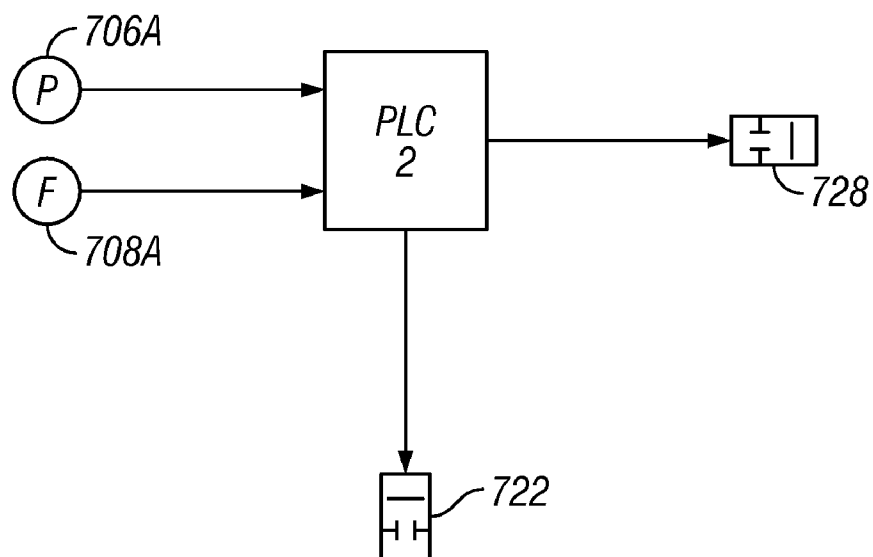


FIG. 12

**PRESSURE SAFETY SYSTEM FOR USE
WITH A DYNAMIC ANNULAR PRESSURE
CONTROL SYSTEM**

**CROSS-REFERENCE TO RELATED
APPLICATIONS**

[0001] Priority is claimed from U.S. Provisional Application No. 60/793,488 filed on Apr. 20, 2006.

**STATEMENT REGARDING FEDERALLY
SPONSORED RESEARCH OR DEVELOPMENT**

[0002] Not applicable.

BACKGROUND OF THE INVENTION

[0003] 1. Field of the Invention

[0004] The invention relates generally to the field of drilling boreholes using dynamic annular pressure control devices. More specifically, the invention relates to method for determining borehole fluid control events, such as loss of drilling fluid or formation fluid entry into a borehole when such devices are used.

[0005] 2. Background Art

[0006] The exploration for and production of hydrocarbons from subsurface Earth formations ultimately requires a method to reach and extract the hydrocarbons from the formations. The reaching and extracting are typically performed by drilling a borehole from the Earth's surface to the hydrocarbon-bearing Earth formations using a drilling rig. In its simplest form, a land-based drilling rig is used to support a drill bit mounted on the end of a drill string. The drill string is typically formed from lengths of drill pipe or similar tubular segments connected end to end. The drill string is supported by the drilling rig structure at the Earth's surface. A drilling fluid made up of a base fluid, typically water or oil, and various additives, is pumped down a central opening in the drill string. The fluid exits the drill string through openings called "jets" in the body of the rotating drill bit. The drilling fluid then circulates back up an annular space formed between the borehole wall and the drill string, carrying the cuttings from the drill bit so as to clean the borehole. The drilling fluid is also formulated such that the hydrostatic pressure applied by the drilling fluid is greater than surrounding formation fluid pressure, thereby preventing formation fluids from entering into the borehole.

[0007] The fact that the drilling fluid hydrostatic pressure typically exceeds the formation fluid pressure also results in the fluid entering into the formation pores, or "invading" the formation. To reduce the amount of drilling fluid lost through such invasion, some of the additives in the drilling fluid adhere to the borehole wall at permeable formations thus forming a relatively impermeable "mud cake" on the formation walls. This mud cake substantially stops continued invasion, which helps to preserve and protect the formation prior to the setting of protective pipe or casing in the borehole as part of the drilling process, as will be discussed further below. The formulation of the drilling fluid to exert hydrostatic pressure in excess of formation pressure is commonly referred to as "overbalanced drilling."

[0008] The drilling fluid ultimately returns to the surface, where it is transferred into a mud treating system, generally including components such as a shaker table to remove solids from the drilling fluid, a degasser to remove dissolved gases from the drilling fluid, a storage tank or "mud pit" and

a manual or automatic means for addition of various chemicals or additives to the fluid treated by the foregoing components. The clean, treated drilling fluid flow is typically measured to determine fluid losses to the formation as a result of the previously described fluid invasion. The returned solids and fluid (prior to treatment) may be studied to determine various Earth formation characteristics used in drilling operations. Once the fluid has been treated in the mud pit, it is then pumped out of the mud pit and is pumped into the top of the drill string again.

[0009] The overbalanced drilling technique described above is the most commonly used formation fluid pressure control method. Overbalanced drilling relies primarily on the hydrostatic pressure generated by the column of drilling fluid in the annular space ("annulus") to restrain entry of formation fluids into the borehole. By exceeding the formation pore pressure, the annulus fluid pressure can prevent sudden influx of formation fluid into the borehole, such as gas kicks. When such gas kicks occur, the density of the drilling fluid may be increased to prevent further formation fluid influx into the borehole. However, the addition of density increasing ("weighting") additives to the drilling fluid: (a) may not be rapid enough to deal with the formation fluid influx; and (b) may cause the hydrostatic pressure in the annulus to exceed the formation fracture pressure, resulting in the creation of fissures or fractures in the formation. Creation of fractures or fissures in the formation typically results in drilling fluid loss to the formation, possibly adversely affecting near-borehole permeability of hydrocarbon-bearing formations. In the event of gas kicks, the borehole operator may elect to close annular sealing devices called "blow out preventers" (BOPs) located below the drilling rig floor to control the movement of the gas up the annulus. In controlling influx of a gas kick, after the BOPs are closed, the gas is bled off from the annulus and the drilling fluid density is increased prior to resuming drilling operations.

[0010] The use of overbalanced drilling also affects the depths at which casing must be set during drilling operations. The drilling process starts with a "conductor pipe" being driven into the ground. A BOP stack is typically attached to the top of the conductor pipe, and the drilling rig positioned above the BOP stack. A drill string with a drill bit may be selectively rotated by rotating the entire string using the rig kelly or a top drive, or the drill bit may be rotated independent of the drill string using a drilling fluid powered motor installed in the drill string above the drill bit. As noted above, an operator may drill through the Earth formations ("open hole") until such time as the drilling fluid pressure at the drilling depth approaches the formation fracture pressure. At that time, it is common practice to insert and hang a casing string in the borehole from the surface down to the lowest drilled depth. A cementing shoe is placed on the drill string and specialized cement is displaced through the drill string and out the cementing shoe to travel up the annulus and displace any fluid then in the annulus. The cement between the formation wall and the outside of the casing effectively supports and isolates the formation from the well bore annulus. Further open hole drilling can be carried out below the casing string, with the drilling fluid again providing pressure control and formation protection in the drilled open hole below the bottom of the casing. The casing protects the shallower formations from fracturing induced by the hydrostatic pressure of the drilling fluid when the

density of the fluid must be increased in order to control formation fluid pressures in deeper formations.

[0011] FIG. 1 is an exemplary diagram of the use of drilling fluid density to control formation pressures during the drilling process in an intermediate borehole section. The top horizontal bar represents the hydrostatic pressure exerted by the drilling fluid and the vertical bar represents the total vertical depth of the borehole. The formation fluid (pore) pressure graph is represented by line 10. As noted above, in overbalanced drilling, the drilling fluid density is selected such that its pressure exceeds the formation pore pressure by some amount for reasons of pressure control and borehole stability. Line 12 represents the formation fracture pressure. Borehole fluid pressures in excess of the formation fracture pressure can result in the drilling fluid pressurizing the formation walls to the extent that small cracks or fractures will open in the borehole wall. Further, the drilling fluid pressure overcomes the formation pressure and causes significant fluid invasion. Fluid invasion can result in, among other problems, reduced permeability, adversely affecting formation production. The pressure generated by the drilling fluid and its additives is represented by line 14 and is generally a linear function of the total vertical depth. The hydrostatic pressure that would be generated by the fluid absent any additives, that is by plain water, is represented by line 16.

[0012] In an "open loop" drilling fluid system described above, where the return fluid from the borehole is exposed only to atmospheric pressure, the annular pressure in the borehole is essentially a linear function of the borehole fluid density with respect to depth in the borehole. In the strictest sense this is true only when the drilling fluid is static. In reality the drilling fluid's effective density may be modified during drilling operations due to friction in the moving drilling fluid, however, the resulting annular pressure is generally linearly related to vertical depth.

[0013] In the example of FIG. 1, the hydrostatic pressure 16 of the drilling fluid and the pore pressure 10 generally track each other in the intermediate section of the borehole to a depth of approximately 7000 feet. Thereafter, the pore pressure 10 (pressure of fluids in the pore spaces of the Earth formations) increases at a rate above that of an equivalent column of water in the interval from a depth of 7000 feet to approximately 9300 feet. Such abnormal formation pressures may occur where the borehole penetrates a formation interval having significantly different characteristics than the prior formation. The hydrostatic pressure 14 maintained by the drilling fluid is safely above the pore pressure prior to about 7000 feet. In the 7000-9300 foot interval, the differential between the pore pressure 10 and hydrostatic pressure 14 is significantly reduced, decreasing the margin of safety during drilling operations. A gas kick in this interval may result if the pore pressure exceeds the hydrostatic pressure, with an influx of fluid and gas into the borehole possibly requiring activation of the BOPs. As noted above, while additional weighting material may be added to the drilling fluid to increase its hydrostatic pressure, such will be generally ineffective in dealing with a gas kick due to the time required to increase the fluid density at the kick depth in the borehole. Such time results from the fact that the drilling fluid must be moved through thousands of feet of drill pipe to even reach the bit depth, let alone begin filling the annulus to increase the hydrostatic pressure in the annulus.

[0014] An open loop drilling fluid system is subject to a number of other problems. It will be appreciated that it is necessary to shut off the mud pumps in order to assemble successive drill pipe segments ("joints") to the drill string to increase its length (called "making a connection"), to enable drilling successively deeper Earth formations. When the pumps are shut off, the annular pressure will undergo a negative spike that dissipates as the annular pressure stabilizes. Similarly, when the pumps are turned back on after making a connection, the annular pressure will undergo a positive spike. Such spiking occurs each time a pipe joint is added to or removed from the string. It will be appreciated that these pressure spikes can cause fatigue on the mud cake and borehole wall, and could result in formation fluids entering the borehole or fracturing the formation again leading to a well control event.

[0015] To overcome the foregoing limitations of drilling using an open-loop fluid circulating system, there have been developed a number of drilling systems called "dynamic annular pressure control" (DAPC) systems. One such system is disclosed, for example, in U.S. Pat. No. 6,904,981 issued to van Riet and assigned to Shell Oil Company. The DAPC system disclosed in the '981 patent includes a fluid backpressure system in which fluid discharge from the borehole is selectively controlled to maintain a selected pressure at the bottom of the borehole, and fluid is pumped down the drilling fluid return system to maintain annulus pressure during times when the mud pumps are turned off. A pressure monitoring system is further provided to monitor detected borehole pressures, model expected borehole pressures for further drilling and to control the fluid backpressure system.

[0016] It has been a concern in the industry that the use of DAPC systems such as disclosed in the van Riet '981 patent that plugging of any part of the backpressure system such that discharge of the drilling fluid from the annulus back to the mud tank or pits is restricted may result in damage to the borehole. Another concern expressed in the industry is that failure of the backpressure regulating components to hold the backpressure may result in loss of pressure control over the borehole.

[0017] What is needed is a system to provide backup pressure control in the borehole in the event of failure of components of a DAPC system.

SUMMARY OF THE INVENTION

[0018] One aspect of the invention is a method for controlling formation pressure during the drilling of a borehole through a subterranean formation. A method according to this aspect includes selectively pumping a drilling fluid through a drill string extended into a borehole, out a drill bit at the bottom end of the drill string, and into an annular space between drill string and the borehole. The drilling fluid is discharged to a reservoir to clean the drilling fluid for reuse. Annular space fluid pressure is selectively increased to maintain a selected fluid pressure proximate the bottom of the borehole by applying fluid pressure to the annular space. The selective increasing includes controlling an aperture of an orifice operatively coupled between the annular space and the reservoir. Fluid from the annular space is discharged other than through the orifice when the annular space fluid pressure exceeds a selected value, or drops below a selected value.

[0019] Other aspects and advantages of the invention will be apparent from the following description and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] FIG. 1 is a graph depicting annular pressures and formation pore and fracture pressures.

[0021] FIGS. 2A and 2B are plan views of two different embodiments of the apparatus that can be used with a method according to the invention.

[0022] FIG. 3 is a block diagram of the pressure monitoring and control system used in the embodiment shown in FIG. 2.

[0023] FIG. 4 is a functional diagram of the operation of the pressure monitoring and control system.

[0024] FIG. 5 is a graph showing the correlation of predicted annular pressures to measured annular pressures.

[0025] FIG. 6 is a graph showing the correlation of predicted annular pressures to measured annular pressures depicted in FIG. 5, upon modification of certain model parameters.

[0026] FIG. 7 is a graph showing how the DAPC system may be used to control variations in formation pore pressure in an overbalanced condition;

[0027] FIG. 8 is a graph depicting DAPC operation as applied to at balanced drilling.

[0028] FIGS. 9A and 9B are graphs depicting how the DAPC system may be used to counteract annular pressure drops and spikes that accompany pump off/pump on conditions.

[0029] FIG. 10 shows another embodiment of a DAPC system that uses only rig mud pumps for providing selected fluid pressure to both the drill string and the annulus.

[0030] FIG. 11 shows one embodiment of a pressure safety system that can be used with a DAPC system.

[0031] FIG. 12 shows another embodiment of the safety system of FIG. 11 that includes a stand-alone controller.

DETAILED DESCRIPTION

[0032] 1. Drilling Circulation System and First Embodiment of a Backpressure Control System

[0033] FIG. 2A is a plan view depicting a land-based drilling system having one embodiment of a dynamic annular pressure control (DAPC) system that can be used with the invention. It will be appreciated that an offshore drilling system may likewise have a DAPC system using methods according to the invention. The drilling system 100 is shown including a drilling rig 102 that is used to support drilling operations. Many of the components used on the drilling rig 102, such as the kelly, power tongs, slips, draw works and other equipment are not shown separately in the Figures for clarity of the illustration. The rig 102 is used to support a drill string 112 used for drilling a borehole through Earth formations such as shown as formation 104. As shown in FIG. 2A the borehole 106 has already been partially drilled, and a protective pipe or casing 108 set and cemented 109 into place in part of the drilled portion of the borehole 106. In the present embodiment, a casing shutoff mechanism, or downhole deployment valve, 110 is installed in the casing 108 to optionally shut off the annulus and effectively act as a valve to shut off the open hole section of the borehole 106

(the portion of the borehole 106 below the bottom of the casing 108) when a drill bit 120 is located above the valve m110.

[0034] The drill string 112 supports a bottom hole assembly (BHA) 113 that can include the drill bit 120, a mud motor 118, a measurement- and logging-while-drilling (MWD/LWD) sensor suite 119 that preferably includes a pressure transducer 116 to determine the annular pressure in the borehole 106. The drill string 112 includes a check valve to prevent backflow of fluid from the annulus into the interior of the drill string 112. The MWD/LWD suite 119 preferably includes a telemetry package 122 that is used to transmit pressure data, MWD/LWD sensor data, as well as drilling information to be received at the Earth's surface. While FIG. 2A illustrates a BHA utilizing a mud pressure modulation telemetry system, it will be appreciated that other telemetry systems, such as radio frequency (RF), electromagnetic (EM) or drill string transmission systems may be used with the present invention.

[0035] As noted in the Background section above, the drilling process requires the use of a drilling fluid 150, which is typically stored in a reservoir 136. The reservoir 136 is in fluid communications with one or more rig mud pumps 138 which pump the drilling fluid 150 through a conduit 140. The conduit 140 is connected to the uppermost segment or "joint" of the drill string 112 that passes through a rotating control head or "rotating BOP" 142. A rotating BOP 142, when activated, forces spherically shaped elastomeric sealing elements to rotate upwardly, closing around the drill string 112 and isolating the fluid pressure in the annulus, but still enabling drill string rotation. Commercially available rotating BOPs, such as those manufactured by National Oilwell Varco, 10000 Richmond Avenue, Houston, Tex. 77042 are capable of isolating annular pressures up to 10,000 psi (68947.6 kPa). The fluid 150 is pumped down through an interior passage in the drill string 112 and the BHA 113 and exits through nozzles or jets in the drill bit 120, whereupon the fluid 150 circulates drill cuttings away from the bit 120 and returns the cuttings upwardly through the annular space 115 between the drill string 112 and the borehole 106 and through the annular space formed between the casing 108 and the drill string 112. The fluid 150 ultimately returns to the Earth's surface and goes through a diverter 117, through conduit 124 and various surge tanks and telemetry receiver systems (not shown separately).

[0036] Thereafter the fluid 150 proceeds to what is generally referred to herein as a backpressure system 131. The fluid 150 enters the backpressure system 131 and flows through a flowmeter 126. The flow meter 126 may be a mass-balance type or other high-resolution flowmeter. Utilizing measurements from the flowmeter 126, a system operator will be able to determine how much fluid 150 has been pumped into the well through the drill string 112, and the amount of fluid 150 returning from the borehole 106. Based on differences between the amount of fluid 150 pumped and fluid 150 returned, the system operator is able to determine whether fluid 150 is being lost to the formation 104, which may indicate that formation fracturing or breakdown has occurred, i.e., a significant negative fluid differential. Likewise, a significant positive differential would be indicative of formation fluid entering into the borehole 106 from the Earth formations 104.

[0037] The returning fluid 150 proceeds to a wear resistant, controllable orifice choke 130. It will be appreciated

that there exist chokes designed to operate in an environment where the drilling fluid **150** contains substantial drill cuttings and other solids. Choke **130** is preferably one such type and is further capable of operating at variable pressures, variable openings or apertures, and through multiple duty cycles. The fluid **150** exits the choke **130** and flows through a valve **121**. The fluid **150** can then be processed by an optional degasser **1** and by a series of filters and shaker table **129**, designed to remove contaminants, including drill cuttings, from the fluid **150**. The fluid **150** is then returned to the reservoir **136**. A flow loop **119A**, is provided in advance of a three-way valve **125** for conducting fluid **150** directly to the inlet of a backpressure pump **128**. Alternatively, the backpressure pump **128** inlet may be provided with fluid from the reservoir **136** through conduit **119B**, which is in fluid communication with the trip tank. The trip tank is normally used on a drilling rig to monitor drilling fluid gains and losses during pipe tripping operations (withdrawing and inserting the full drill string or substantial subset thereof from the borehole). In the invention, the trip tank functionality is preferably maintained. The three-way valve **125** may be used to select loop **119A**, conduit **119B** or to isolate the backpressure system. While the backpressure pump **128** is capable of utilizing returned fluid to create a backpressure by selection of flow loop **119A**, it will be appreciated that the returned fluid could have contaminants that would not have been removed by filter/shaker table **129**. In such case, the wear on backpressure pump **128** may be increased. Therefore, the preferred fluid supply for the backpressure pump **128** is conduit **119A** to provide reconditioned fluid to the inlet of the backpressure pump **128**.

[0038] In operation, the three-way valve **125** would select either conduit **119A** or conduit **119B**, and the backpressure pump **128** is engaged to ensure sufficient flow passes through the upstream side of the choke **130** to be able to maintain backpressure in the annulus **115**, even when there is no drilling fluid flow coming from the annulus **115**. In the present embodiment, the backpressure pump **128** is capable of providing up to approximately 2200 psi (15168.5 kPa) of pressure; though higher pressure capability pumps may be selected at the discretion of the system designer.

[0039] The ability to provide backpressure is a significant improvement over normal fluid control systems. The pressure in the annulus provided by the fluid is a function of its density and the true vertical depth and is generally a by approximation linear function. As noted above, additives added to the fluid in reservoir **136** must be pumped downhole to eventually change the pressure gradient applied by the fluid **150**.

[0040] The system can include a flow meter **152** in conduit **100** to measure the amount of fluid being pumped into the annulus **115**. It will be appreciated that by monitoring flow meters **126**, **152** and thus the volume pumped by the backpressure pump **128**, it is possible to determine the amount of fluid **150** being lost to the formation, or conversely, the amount of formation fluid entering to the borehole **106**. Further included in the system is a provision for monitoring borehole pressure conditions and predicting borehole **106** and annulus **115** pressure characteristics.

[0041] FIG. 2B shows an alternative embodiment of the DAPC system. In this embodiment the backpressure pump is not required to maintain sufficient flow through the choke when the flow through the borehole needs to be shut off for any reason. In this embodiment, an additional three-way

valve **6** is placed downstream of the drilling rig mud pumps **138** in conduit **140**. This valve **6** allows fluid from the rig mud pumps **138** to be completely diverted from conduit **140** to conduit **7**, thus diverting flow from the rig pumps **138** that would otherwise enter the interior passage of the drill string **112**. By maintaining action of rig pumps **138** and diverting the pumps' **138** output to the annulus **115**, sufficient flow through the choke to control annulus backpressure is ensured.

[0042] 2. DAPC Monitoring System

[0043] FIG. 3 is a block diagram of the pressure monitoring system **146** of the DAPC system. System inputs to the pressure monitoring system **146** include the downhole pressure **202** that has been measured by the appropriate sensor in MWD/LWD sensor package **119**, transmitted to the Earth's surface by the MWD telemetry package **122** and received by transducer equipment (not shown) at the Earth's surface. Other system inputs include pump pressure **200**, input flow **204** from flow meter **152**, drilling penetration rate and drill string rotation rate, as well as axial force on the drill bit ("weight on bit" or WOB) and torque on the drill bit (TOB) that may be transmitted from suitable sensors (not shown separately) the BHA **113**. Return mud flow is measured using flow meter **126**. Signals representative of the various data inputs are transmitted to a control unit **230**, which itself includes a drill rig control unit **232**, a drilling operator's station **234**, a DAPC processor **236** and a back pressure programmable logic controller (PLC) **238**, all of which can be connected by a common data network **240**. The DAPC processor **236** serves three functions, monitoring the state of the borehole pressure during drilling operations, predicting borehole response to continued drilling, and issuing commands to the backpressure PLC to control the aperture of the choke **130** and to selectively operate the backpressure pump **128**. The specific logic associated with the DAPC processor **236** will be discussed further below.

[0044] 3. Calculation of Backpressure

[0045] A schematic model of the functionality of the DAPC pressure monitoring system **146** is shown in FIG. 4. The DAPC processor **236** includes programming to carry out "Control" functions and "Real Time Model Calibration" functions. The DAPC processor **236** receives data from the various sources and continuously calculates in real time the correct backpressure set-point based on the values of the input parameters. The backpressure set-point is then transferred to the programmable logic controller **238**, which generates control signals for the backpressure pump **128** and the choke **130**. The input parameters fall into three main groups. The first are relatively fixed parameters **250**, including parameters such as borehole and casing string geometry, drill bit nozzle diameters, and borehole trajectory. While it is recognized that the actual borehole trajectory may vary from the planned trajectory, the variance may be taken into account with a correction to the planned trajectory. Also within this group of parameters are temperature profile of the drilling fluid in the annulus (**115** in FIG. 2A) and the drilling fluid composition. As with the trajectory parameters, these are generally known and do not substantially change over small portions of the course of the borehole drilling operations. In particular, with the DAPC system, one objective is to be able to keep the fluid **150** density and composition relatively constant notwithstanding changes in forma-

tion fluid pressure, by using the backpressure system to provide the additional pressure to control the annulus pressure.

[0046] The parameters in the second group of parameters 252 are variable in nature and are sensed and logged substantially in real time. The common data network 240 provides these data to the DAPC processor 236. These data includes flow rate data provided by both downhole and return flow meters 152 and 126, respectively, the drill string rate of penetration (ROP) or axial velocity, the drill string rotational speed, the drill bit depth, and the borehole depth, the latter two being derived from data from well known drilling rig sensors. The last parameter is the downhole pressure 254 that is provided by the downhole MWD/LWD sensor suite 119 and can be transmitted to the Earth's surface using the mud pulse telemetry package 122. One other input parameters is the set-point downhole pressure 256, that is, the desired annulus pressure.

[0047] Functionally, the control module 258 attempts to calculate the pressure in the annulus (115 in FIG. 2A) at each point over its full borehole length, utilizing various models designed for various formation and fluid parameters. The pressure in the annulus is a function not only of the hydrostatic pressure or weight of the fluid column in the borehole, but includes the pressures caused by drilling operations, including fluid displacement by the drill string, frictional losses returning up the annulus, and other factors. In order to calculate the pressure within the well, the programming in the control module 258 considers the borehole as a finite number of segments, each assigned to a segment of borehole length. In each of the segments the dynamic pressure and the fluid weight (hydrostatic pressure) is calculated and are used to determine the pressure differential 262 for the segment. The segments are then summed and the pressure differential for the entire borehole profile is determined.

[0048] It is known that the flow rate of the fluid 150 being pumped into the borehole is proportional to the flow velocity of the fluid 150 and the velocity may thus be used to determine dynamic pressure loss as the fluid 150 is being pumped into the borehole through the drill string. The fluid 150 density is calculated in each segment, taking into account the fluid compressibility, estimated drill cuttings loading and the thermal expansion of the fluid 150 for the specified segment, which is itself related to the temperature profile for that segment of the borehole. The fluid viscosity at the estimated temperature for the segment is also important for determining dynamic pressure losses for the segment. The composition of the fluid is also considered in determining compressibility and the thermal expansion coefficient. The drill string rate of axial movement is related to "surge" and "swab" pressures encountered during drilling operations as the drill string is moved into or out of the borehole. The drill string rotation is also used to determine dynamic pressures, as rotation creates a frictional force between the fluid in the annulus and the drill string. The drill bit depth, borehole depth, and borehole and drill string geometry are all used to help generate the borehole segments to be modeled. In order to calculate the weight of the fluid, the present embodiment considers not only the hydrostatic pressure exerted by fluid 150, but also the fluid compression, fluid thermal expansion and the drill cuttings loading of the fluid observed during drilling operations. It will be appreciated that the cuttings loading can be determined as the fluid is returned to the surface and reconditioned for further use.

All of these factors can be used in calculation of the "static pressure" of the fluid in the annulus.

[0049] Dynamic pressure calculation includes many of the same factors in determining static pressure. However, dynamic pressure calculation further considers a number of other factors. Among them is whether the fluid flow is laminar or turbulent. Whether the flow is laminar or turbulent is related to the estimated roughness, borehole size and the flow velocity of the fluid. The calculation also considers the specific geometry for the segment in question. This would include borehole eccentricity and specific drill string segment geometry (e.g. threaded connection or "box/pin" upsets) that affect the flow velocity observed in any segment of the borehole annulus. The dynamic pressure calculation further includes cuttings accumulation in the borehole, as well as fluid rheology and the drill string movement's (axial and rotational) effect on dynamic pressure of the fluid.

[0050] The pressure differential 262 for the entire annulus is calculated and compared to the set-point pressure 251 in the control module 264. The desired backpressure 266 is then determined and conducted to programmable logic controller 238, which generates control signals for the backpressure pump 128 and the choke 130. Generally, backpressure is increased by reducing the choke aperture. Backpressure is decreased by increasing the choke aperture. As will be explained in more detail below, the particular choke aperture extant at any time can be used as an indicator that a well control event is taking place, namely, that formation fluid is entering the borehole from one or more of the formations (a "kick"), or drilling fluid is leaving the borehole and entering one or more of the formations adjacent to the borehole ("lost circulation").

[0051] 4. Calibration and Correction of the Backpressure

[0052] The above discussion of how backpressure is generally calculated uses several downhole parameters, including downhole pressure and estimates of fluid viscosity and fluid density. These parameters are determined downhole and are typically transmitted up the mud column using mud pressure pulses. Because the data bandwidth for mud pulse telemetry is very low and the bandwidth is also used by other MWD/LWD functions, as well as drill string control functions, downhole pressure, fluid density and viscosity essentially cannot be input to the DAPC model on a real time basis. Accordingly, it will be appreciated that there is likely to be a difference between the measured downhole pressure, when transmitted up to the surface using the mud pulse telemetry, and the predicted downhole pressure for that depth. When such occurs the DAPC system computes adjustments to the parameters and implements them in the model to make a new best estimate of downhole pressure. The corrections to the model may be made by varying any of the variable parameters. In the present embodiment, the fluid density and the fluid viscosity are modified in order to correct the predicted downhole pressure. Further, in the present embodiment the actual downhole pressure measurement is used only to calibrate the calculated downhole pressure, rather than to predict downhole annular pressure. If downhole telemetry bandwidth is improved in the future to enable essentially real-time transmission of the pressure and temperature near the bottom of the borehole, it may then be practical to include real-time downhole pressure and temperature information to correct the model.

[0053] Because there is a delay between the measurement of downhole pressure and other real time inputs, the DAPC

control system 236 further operates to index the inputs such that real time inputs properly correlate with delayed downhole transmitted inputs. The rig sensor inputs, calculated pressure differential and backpressure pressures, as well as the downhole measurements, may be “time-stamped” or “depth-stamped” such that the inputs and results may be properly correlated with later received downhole data. Using a regression analysis based on a set of recently time-stamped actual pressure measurements, the model may be adjusted to more accurately predict actual pressure and the required backpressure.

[0054] FIG. 5 depicts the operation of the DAPC control system demonstrating an uncalibrated DAPC model. It will be noted that the downhole pressure while drilling (PWD) 400 is shifted in time as a result of the time delay for the signal to be selected and transmitted uphole. As a result, there exists a significant offset between the DAPC predicted pressure 404 and the non-time stamped pressure while drilling or annular pressure (PWD) measurement 400. When the PWD is time stamped and shifted back in time 402, the differential between PWD 402 and the DAPC predicted pressure 404 is significantly less when compared to the non-time shifted PWD 400. Nonetheless, the DAPC predicted pressure differs significantly. As noted above, this differential is addressed by modifying the model inputs for fluid 150 density and viscosity. Based on the new estimates, in FIG. 6, the DAPC predicted pressure 404 more closely tracks the time stamped PWD 402. Thus, the DAPC model uses the PWD to calibrate the predicted pressure and modify model inputs to more accurately predict downhole pressure throughout the entire borehole profile.

[0055] Based on the DAPC predicted pressure, the DAPC control system 236 will calculate the required backpressure level 266 and transmit it to the programmable logic controller 240. The programmable controller 240 then generates the necessary control signals to choke 130, valves 121 and 123, and backpressure pump 128.

[0056] In a particular embodiment, calculation of the DAPC system predicted borehole pressure is delayed, after each time the rig mud pumps are started, at least until the pressure of the drilling mud at the mud pump outlet is at least equal to the backpressure extant at the inlet to the choke. The purpose for the present embodiment is to overcome several adverse artifacts in pressure modeling caused by charging of the mud circulation system after restarting the rig mud pumps. It will be appreciated that when the rig mud pumps are first started, such as after adding a new segment of drill pipe to the drill string (“making a connection”), a substantial quantity of drilling mud will be added to the total drill string and borehole circulation system volume due to compression of the mud when it is pressurized by the rig mud pumps to the degree necessary to overcome all the friction in the circulation system. The present embodiment may have particular benefit in the case where a flowmeter is not available in the fluid discharge circuit of the borehole.

[0057] In another particular embodiment, pressure in the annulus may be measured at a plurality of different depths by using pressure sensors disposed at spaced apart locations along the drill string. Such distributed pressure sensors may be similar to those disposed in data repeater devices in a “wired” drill string such as one sold under the trademark INTELLIPIPE, which is a trademark of Grant Prideco, L.P., Houston, Tex. Typically, the INTELLIPIPE system includes a data repeater, which may have included temperature and

pressure sensors, every 1,000 feet along the drill string. The system may include a pressure sensor proximate the bottom of the drill string just as with conventional “pressure while drilling” measuring instruments. In the present embodiment, by having pressure measurements made at a plurality of positions along the borehole, the hydraulics model may be calibrated for a number of different effects, including variations in borehole geometry that may result from washout or the like, changes in fluid temperature, fluid viscosity and/or fluid density as a result of fluid entry into the borehole or temperature changes resulting from changes in drilling fluid flow rate within the borehole. Pressure measurements made at a plurality of different positions along the borehole may also provide indication of the existence of fluid entry into the borehole from one or more of the Earth formations adjacent the borehole. Fluid pressure at one or more of the measurement positions that is at variance with a predicted pressure from the hydraulics model may indicate fluid entry into the borehole, and may be able to determine whether the fluid entering the borehole is water, oil, gas or mixtures thereof.

[0058] From the foregoing description, it may be readily inferred that the predicted pressure may be based on drilling fluid flow rate and drill string fluid pressure, and expected borehole geometry among other factors.

[0059] 5. Applications of the DAPC System

[0060] The advantage in using the DAPC controlled backpressure system may be readily observed in the chart of FIG. 7. The hydrostatic pressure of the fluid is depicted by line 302. As may be seen, the hydrostatic pressure increases as a linear function of the depth of the borehole according to the formula:

$$P = \rho g TVD + C \quad (1)$$

[0061] where P is the pressure, ρ is the fluid specific gravity, TVD is the total vertical depth of the borehole, g is the Earth’s gravitational constant and C is the backpressure supplied by the backpressure system. In the instance of water gradient hydrostatic pressure 302, the density of the fluid is that of water. Moreover, in an open circulation system, the backpressure C is always zero. In order to ensure that the annular pressure 303 is in excess of the formation pore pressure 300, the fluid is weighted (its density is increased), thereby increasing the pressure applied with respect to the depth in the borehole. The pore pressure profile 300 can be seen in FIG. 7 as being linear, until such time as it exits casing 301, in which instance, it is exposed to the actual formation pressure, resulting in a sudden increase in formation pressure. In normal operations, the fluid density must be selected such that the annular pressure 303 exceeds the formation pore pressure below the casing 301.

[0062] By contrast, the use of the DAPC controlled backpressure system permits an operator to make essentially step changes in the annular pressure. Multiple DAPC pressure lines 304, 306, 308 and 310 are shown in FIG. 7. In response to the increase observed in the pore pressure at 300b, the back pressure C may be increased to increase the annular pressure from 304 to 306 to 308 to 310 in response to increasing pore pressure 300b, in contrast with normal annular pressure techniques as depicted in line 303. The DAPC system further offers the advantage of being able to decrease the back pressure in response to a decrease in pore pressure as shown in 300c. It will be appreciated that the difference between the DAPC-maintained annular pressure

310 and the pore pressure **300c**, known as the overbalance pressure, can be significantly less than the overbalance pressure seen using conventional pressure control methods **303**. Highly overbalanced conditions can adversely affect the formation permeability by forcing greater amounts of borehole fluid into the formation.

[0063] FIG. 8 is a graph depicting one application of the DAPC system in an at-balance drilling (ABD), or near ABD, environment. The situation in FIG. 8 shows the pore pressure gradient in an interval **320a** as being substantially linear until approximately 2 km TVD, and the fluid in the formations as being kept in check by conventional annular pressure **321a**. At 2 km TVD a sudden increase in pore pressure occurs, as shown at **320b**. Utilizing pressure control techniques known in the art, the procedure would be to increase the fluid density to prevent formation fluid influx and sloughing off of the borehole mud cake. The resulting increase in density modifies the pressure gradient of the fluid to that shown at **321b**. However, in doing so it dramatically increases the overbalance pressure, not only in region **320c**, but in region **320a** as well.

[0064] Using the DAPC system, the technique to control the borehole in view of the pressure increase observed at **320b** is to apply backpressure to the fluid in the annulus to shift the entire annulus pressure profile to the right, such that pressure profile **322** more closely matches the pore pressure **320c**, as opposed to that presented by pressure profile **321b**.

[0065] The DAPC system for pressure control may also be used to control a major well control event, such as a fluid influx. Under methods known in the art, in the event of a large formation fluid influx, such as a gas kick, the only practical borehole pressure control procedure was to close the BOPs to effectively hydraulically “shut in” (seal) the borehole, relieve excess annulus pressure through a choke and kill manifold, and weight up the drilling fluid to provide additional annular pressure. This technique requires time to bring the well under control. An alternative method is sometimes called the “driller’s method”, which uses continuous drilling fluid circulation without shutting in the borehole. A supply of heavily weighted fluid, e.g., 18 pounds per gallon (ppg) (3.157 kg/l) is constantly available during drilling operations below any set casing. When a gas kick or formation fluid influx is detected, the heavily weighted fluid is added and circulated downhole, causing the influx fluid to go into solution in the circulating fluid. The influx fluid starts coming out of solution upon reaching the casing shoe and is released through the choke manifold. It will be appreciated that while the Driller’s method provides for continuous circulation of fluid, it may still require additional circulation time without drilling ahead, to prevent additional formation fluid influx and to permit the formation fluid to go into circulation with the now higher density drilling fluid.

[0066] Utilizing the present DAPC technique, when a formation fluid influx is detected, the backpressure is increased, as opposed to adding heavily weighted fluid. Like the driller’s method, the mud circulation is continued. With the increase in annulus pressure, the formation fluid influx goes into solution in the circulating fluid and is released via the choke manifold. Because the pressure has been increased, it is no longer necessary to immediately circulate a heavily weighted fluid. Moreover, as a result of the fact that the backpressure is applied directly to the annulus, the

formation fluid is quickly forced to go into solution, as opposed to waiting until the heavily weighted fluid is circulated into the annulus.

[0067] An additional application of the DAPC technique relates to its use in non-continuous circulating systems. As noted above, continuous circulation systems are used to help stabilize the formation, avoiding the sudden pressure **502** drops that occurs when the mud pumps are turned off to make/break new pipe connections. This pressure drop **502** is subsequently followed by a pressure spike **504** when the pumps are turned back on for drilling operations. This is depicted in FIG. 9A. These variations in annular pressure **500** can adversely affect the borehole mud cake, and can result in fluid invasion into the formation. As shown in FIG. 9B, the DAPC system backpressure **506** may be applied to the annulus upon shutting off the mud pumps, ameliorating the sudden drop in annulus pressure from pump off condition to a more mild pressure drop **502**. Prior to turning the pumps on, the backpressure may be reduced such that the pump on condition spike **504** is likewise reduced. Thus the DAPC backpressure system is capable of maintaining a relatively stable downhole pressure during drilling conditions.

[0068] 6. Determining Well Control Events with the DAPC System

[0069] It has been determined that a DAPC system such as the one explained above with reference to FIGS. 2A through 9B, and one that will be further explained below with reference to FIG. 10, can be used to determine the existence of well control events. Well control events include influx of fluid from the Earth formations surrounding the borehole, and efflux of fluid in the borehole into the surrounding formations. An influx event (called a “kick”) can be detected by comparing the calculated down hole pressure to the actual down hole pressure. Calculating the down hole pressure can be performed using a hydraulics model that determines down hole pressure based on an expected fluid density in the borehole, usually the density of the drilling fluid as pumped through the drill string. The actual recorded down hole pressure is typically measured near to the drill bit as with an annular pressure sensor or some other form of bottom hole pressure measurement that measures the actual down hole pressure.

[0070] Should an influx occur and there is a density contrast between the influx fluid and the drilling fluid that is in the borehole, the model-calculated and the actual borehole down hole pressures will diverge as a result of the difference in the calculated pressure of the column of fluid and the actual pressure as measured, whether the column is static or dynamic. This divergence can be recorded as an error by the DAPC system and corrective action can be taken to maintain the down hole pressure at the desired value (the set point pressure) by either reducing the aperture of the choke if the density of the influx is less than the density of the fluid in the well, or increasing the aperture of the choke somewhat if the density of the influx is greater than the density of the fluid in the well. Change in the choke aperture resulting from such bottom hole pressure differences, when there is no change in the pumped fluid flow rate, is used as an indicator that an influx has taken place.

[0071] Another characteristic of an influx is that the choke aperture may increase somewhat due to the increased fluid discharge rate at the Earth’s surface, and then stabilize at a new aperture, which may be less, greater or the same as the

immediately prior choke aperture, depending on the influx fluid density. If the influx continues and the density is less than the drilling fluid, the average density of the fluid in the borehole will continue to decrease and the choke aperture will continue to close in response to the DAPC system attempting to maintain the down hole pressure at the set point value. Conversely, if the influx fluid density is greater than the borehole fluid density, as fluid influx continues, the density of the fluid column in the borehole annulus will increase, continuing to reduce the surface pressure in the annulus, and thus causing the DAPC system to continue to increase the choke aperture.

[0072] The DAPC system determines the new choke aperture based on an adjustment of the predicted down hole pressure with respect to the actual measured down hole pressure. In the case of a lower density fluid influx, the predicted down hole pressure will be less than the previous prediction because the fluid influx has continued to reduce the average density of the column of fluid in the annulus. This will continue to indicate an error and the DAPC system will correct for the error by continuing to close the choke for so long as the influx continues and the average density in well bore continues to decrease. For the case of the influx fluid having a higher density than the drilling fluid, for example, influx from a salt water zone when drilling with an oil-based drilling fluid, the DAPC system will open the choke aperture to reduce the surface annulus pressure in order to compensate for the increasing density of the fluid in the annulus for so long as the influx continues and the average density is increasing.

[0073] The only other case is when the density of the influx is practically equal to the extant borehole fluid density. In this case the choke may open somewhat due to the increase in discharge volume and then continue at the new aperture or a new averaged aperture (due to choke aperture fluctuation using the PID controller 238, such fluctuation being typically sinusoidal). The DAPC system will produce an error that the choke aperture has changed without changes calculated by the hydraulics model since the model is using a number of standard parameters to calculate down hole pressure, one of which is the pump rate. So long as the pump rate does not change, or a change in the pump rate has not indicated that the choke aperture is to be changed by the DAPC system, an error will result. Therefore, a sustained increase in choke aperture for no other apparent reason may be inferred to be a kick when the density of the incoming formation fluid is substantially the same as the drilling mud.

[0074] 7. Alternative Embodiment of Backpressure Control System Using Only Rig Mud Pumps

[0075] It is also possible to provide selected, controlled annulus fluid pressure without the need for an additional pump to supply back pressure to the annulus when such back pressure must be generated by a pump, as explained above with reference to FIG. 2B. Another embodiment of a back-pressure system that uses the rig mud pumps is shown in schematic form in FIG. 10. The rig mud pump(s), shown at 138 discharge drilling mud at selected flow rates and pressures, as is ordinarily performed during drilling operations. In the present embodiment, a first flowmeter 152 may be disposed in the drilling mud flow path downstream of the pump(s) 138. The first flowmeter 152 may be used to measure the flow rate of the drilling fluid as it is discharged from the pump(s) 138. Alternatively, a familiar "stroke counter", that estimates mud discharge volume by monitor-

ing movement of the pump(s) may be used to estimate the total flow rate from the pump(s) 138. The drilling fluid flow is then applied to a first controllable orifice choke 130A, the outlet of which is ultimately coupled to the standpipe 602 (which is itself coupled to the inlet to the interior passage in the drill string). During regular drilling operations, the first choke 130A is ordinarily fully opened.

[0076] Drilling fluid discharge from the pump(s) 138 is also coupled to a second controllable orifice choke 130B, the outlet of which is ultimately coupled to the well discharge (the annulus 604). As in previously described embodiments, the interior of the well is sealed by a rotating control head or spherical BOP, shown at 142. Not shown in FIG. 10 are the drill string and other components in the well located below the rotating control head 602, because they can be essentially identical to those used in other embodiments, particularly such as shown in FIG. 2. A third controllable orifice choke 130 can be coupled between the annulus 604 and the mud tank or pit (136 in FIG. 2) and controls the rate at which the drilling mud leaves the well so as to maintain a selected back pressure on the annulus, similarly to what is performed in the previously described embodiments.

[0077] The first 130A and second 130B controllable orifice chokes may each include downstream thereof a respective flow meter 152A, 152B. In conjunction with either the stroke counter (not shown) or the first flowmeter 152 on the pump discharge, the flow rate of drilling fluid from the pump(s) 138 into the standpipe and into the annulus may be determined. The flowmeters 152, 152A, 152B are shown as having their respective signal outputs coupled to the PLC 238 in the DAPC unit 236, which may be essentially the same as the corresponding devices shown in FIG. 3. Control outputs from the PLC 238 are provided to operate the three controllable orifice chokes 130, 130A, 130B.

[0078] For purposes of making or breaking connections in the drill string during operation, it is necessary to release all the fluid pressure at the top of the drill string, while it may be necessary to continue to maintain fluid pressure to the top of the annulus 604. To perform the necessary pressure functions, the PLC 238 may operate the first controllable orifice choke 130A to completely close. Then, a bleed off or "dump" valve 600, which may be under operative control of the PLC 238, is opened to release all the drilling fluid pressure. The check valve or one way valve in the drill string retains pressure below it in the drill string. Thus, connections may be made or broken to lengthen or shorten the drill string during drilling operations.

[0079] During such connection operations, selected fluid pressure on the annulus is maintained by controlling the operation of the pump(s) 138, and the second 130B and third 130 controllable orifice chokes. Such control may be performed automatically by the PLC 238.

[0080] During regular drilling operations, the correct fluid pressure is maintained on the annulus 604, using the same hydraulics model as in the previous embodiments, by selectively diverting a portion of the pump(s) 138 flow into the annulus 604 by controlling the orifices of the first 130A and second 130B chokes, and by controlling discharge from the well by controlling the orifice of the third choke 130. Ordinarily during drilling, the second choke 130B may remain closed, such that back pressure on the well is maintained entirely by control of the orifice of the third choke 130, similar to the manner in which back pressure is maintained according to the previous embodiments. Ordi-

narily, it is contemplated that the second choke **130B** will be opened during connection procedures to maintain back pressure, similar to the times at which the back pressure pump in the previous embodiments would be operated.

[0081] The present embodiment advantageously eliminates the need for a separate pump to maintain back pressure. The present embodiment may have additional advantages over the embodiment shown in FIG. 2B which uses a three-way valve to diver mud flow from the rig mud pumps to maintain back pressure, the most important of which is that connections can be made without the need to stop the rig mud pumps.

[0082] Depending on the particular equipment configuration, it may be possible to determine mud flow rate into the annulus **604** using the stroke counter (not shown) and the third flowmeter **152B**, or using the first and second flowmeters **152**, **152A**, respectively.

[0083] 8. Controlling Backpressure in Response to a Prediction of Formation Fluid Pressure

[0084] The foregoing embodiments of a dynamic annular pressure control system and methods for controlling fluid pressure in a borehole generally operate on the principle that the bottom hole pressure required to control the fluid pressure in the subterranean formations is known. As will be readily appreciated by those skilled in the art, prior knowledge of the formation fluid pressure may be obtained from a number of sources. In so-called "normally pressured" formations, the fluid pressure in the formations is substantially the same as the fluid pressure of a column of water having the same height as the true vertical depth in the wellbore under consideration. Normally pressured formations occur where the formations have some form of pressure conduit to the Earth's surface, such that compression of the formations by the weight of layers of rock thereabove (called "overburden") can be hydraulically communicated to the Earth's surface. Compression of the formations results in reduction of the fractional volume of pore space to less than what was extant at the time the rock was deposited. Such reduction in fractional volume of pore space compresses the fluid in the pore spaces. If the fluid is in hydraulic communication with the Earth's surface, then the reduction in pore space is not accompanied by any increase in fluid pressure. However, in many depositional environments, certain layers of rock deposited above a porous, permeable Earth formation may be impermeable, thus closing hydraulic communication with the Earth's surface. In such cases, the weight of the overburden may be increasingly borne by the fluid itself, as well as the solid rock material ("matrix"). Where the fluid bears increasing amounts of the overburden load, the fluid pressure in the subterranean formations may increase to well beyond that of an equivalent height water column. Such elevated formation pressures are known as "overpressures" or "abnormal formation pressures." One object of controlling fluid pressure in the borehole using the DAPC system according to the various embodiments described herein is to control abnormal formation pressures by maintaining a suitable bottom hole pressure in the borehole.

[0085] Accordingly, in a particular implementation, one or more techniques may be used to predict the formation fluid pressure at a depth below that to which the wellbore has already been drilled. The bottom hole pressure maintained by the DAPC system may be adjusted in response to the predicted formation fluid pressure. As used herein, increas-

ing "depth" in the borehole means that the total length of the borehole extending from the Earth's surface is increased, even if the vertical depth in the Earth to which the borehole extends may or may not be increased correspondingly. As will be appreciated by those skilled in the art, a borehole may increase in depth as defined above without penetrating deeper in the vertical direction when such a borehole is drilled along a substantially horizontal direction. A "depth below that to which the borehole is drilled", therefore, may include for purposes of defining the scope of this invention, a position in the Earth in any position contemplated by the trajectory of the borehole to which the borehole is expected to penetrate, but has not yet so penetrated.

[0086] There are a number of formation fluid pressure estimation techniques known in the art. An important technique is velocity analysis from reflection seismic surveys. A reflection seismic survey includes placing a seismic energy source and one or more seismic receivers proximate the Earth's surface (or water surface if conducted in a marine environment). The source is actuated and a record of signals detected by the receiver, indexed with respect to actuation, time is made. Inferences about the structure and composition are made from events in the record determined to be a result of subsurface acoustic impedance boundaries (usually at formation layer boundaries) in the Earth. Estimates of seismic energy velocity may be made from the travel times of the seismic energy to the various reflectors. The estimates of seismic energy velocity may be used to make an estimate of the formation fluid pressure in the following manner. An ordinary rate of change in seismic velocity ("normal trend") with respect to depth is established from the velocity analysis. Deviations of velocity at certain depths, usually slower than expected velocities determined from the ordinary rate of change are correlated to abnormal formation pressures. The amount of variation from the normal trend has been shown by substantial experience to be directly correlated to an amount of overpressure.

[0087] Other methods known in the art for estimating formation fluid pressure include establishing "normal trends" for electrical resistivity of the Earth formations, and acoustic velocity of the formations. Various types of measuring instruments may be included in the drill string, such as "logging while drilling" devices that include resistivity and/or acoustic travel time sensors. Such sensors make measurements corresponding to formation resistivity and/or acoustic velocity. Such measurements may be communicated to the Earth's surface as explained earlier herein. The measurements may be used at the Earth's surface to estimate the formation fluid pressure at a greater depth ("ahead of the bit") than the borehole is drilled.

[0088] Yet another method for estimating formation fluid pressure includes establishing a normal trend of a factor known as "d-exponent." The d-exponent is also known as normalized rate of penetration and can be calculated by a formula that includes the diameter of the drill bit, the axial force (weight) applied to the drill bit, the rotation rate of the drill bit and the rate of axial movement of the drill string as the formations are drilled. Deviations of the d-exponent from the normal trend are also shown by considerable experience to correspond to the amount of overpressure.

[0089] As may be inferred from the foregoing description, a normal trend for any or all of the above parameters would indicate that as overburden increases, the fractional volume of pore space in the rock decreases as the rock matrix is

compressed into tighter and tighter contact. Therefore, the expectation in a normal trend is for acoustic velocity, seismic velocity and formation resistivity to increase with depth in the Earth, and for the d-exponent to decrease. When some of the overburden load is carried by the formation fluid because it is hydraulically isolated from the Earth's surface, such contact between the matrix components is effectively reduced from what it would otherwise be. Such reduction in rock matrix compression results in lower resistivity and velocity than that predicted by the normal trend, and correspondingly, higher d-exponent.

[0090] A number of pore pressure prediction and analysis techniques are available commercially and may have application with the DAPC system. See, for example a sales brochure entitled, *Pore Pressure Prediction*, Western Geco LLC, Houston, Tex. (2005). See also, *Real Time Pore Pressure Detection Ahead of the Bit*, C. Esmersoy et al., Western Geco LLC, Houston, Tex. (2004).

[0091] 9. Safety Systems for Use with a DAPC System

[0092] FIG. 11 shows one embodiment of a safety system that can be used with the foregoing DAPC system, or any other form of "closed loop" managed pressure drilling system. For purposes of the following description, "closed loop" means drilling such that the rotating diverter, spherical BOP or similar device is used and actuated, such that all drilling fluid returning from the borehole is within a sealed environment until finally discharged into the mud tank or pit. The mud tank 700 holds a supply of drilling fluid, which is drawn through pump intake line 702A to the drilling rig mud pumps 702. The drilling fluid is discharged through discharge line 702B into the interior of the drill string 710. The drill string 710 preferably includes a check valve 704 disposed at a selected position along the string to hold fluid pressure from returning to the mud pumps 702 when the mud pumps 702 are stopped. The drilling fluid exits the drill string 710 at the bottom end thereof through a drill bit 716, and returns to the surface through the annulus 714. In the present embodiment, a rotating diverter, spherical BOP or similar device, shown at 712, that rotatably seals against the drill string 710 hydraulically closes the upper part of the annular space 714. One fluid outlet from the rotating diverter 712 can be coupled to components of a DAPC system, for example, as described above with reference to FIGS. 2A and 2B. Such components may include a fluid pressure sensor 706, and a fluid flowmeter 708 that measure pressure and flow of the drilling fluid. The signals from the sensor 706, 708 are in communication with a programmable logic controller (PLC) 724 or similar device that operatively controls a variable orifice choke 726 to regulate the flow of drilling fluid out of the borehole and back to the mud tank 700. In order to provide backpressure when the rig mud pumps 702 are stopped, the system may include a backpressure pump 718 in fluid communication on its discharge side with the annulus 714, as shown in FIG. 11. The backpressure pump 718 may include a check valve 720 in its outlet line to prevent fluid flow back through the backpressure pump 718 when the backpressure pump 718 is stopped. Operation of the foregoing devices may be substantially as explained above with reference to the DAPC system.

[0093] In the present embodiment, the safety system may provide control over the pressure in the annular space 714 in the event the DAPC system is unable to maintain such control. A shutoff valve 722, which may be solenoid operated, in the present embodiment is disposed between a fluid

outlet of the rotating diverter 712 and the variable choke 726. If the pressure in the annulus 714 is below the pressure required to maintain formation pressure control, and the PLC 724 is attempting to close the variable choke 726, such may be an indication of choke failure in the open position (enabling more fluid flow than required). In such event, the PLC may be programmed to close the shutoff valve 722. Alternatively, as shown in the inset in FIG. 11, the shutoff valve 722 may be substituted by a crossover valve 722A. The outlets of the crossover valve 722A may be selected to place the fluid outlet of the rotating diverter 712 in fluid communication with either the controllable orifice choke 726, or, when switched, a backup controllable orifice choke 726A. The crossover valve 722A would be switched in the event the PLC 724 is attempting to operate the controllable choke 722 but the pressure in the annular space 714 is not within a selected range. In such event, the PLC 724 would operate the crossover valve 722A to connect the fluid outlet of the rotating diverter through the backup controllable orifice choke 726A.

[0094] In the event the PLC 724 is attempting to open the controllable orifice choke 726, and pressure in the annular space 714 exceeds a safe value, to prevent failure of the bore hole, a pressure relief valve 728 may be provided at the same or a different fluid outlet from the rotating diverter 712. In the present embodiment, the pressure relief valve 728 may be manually set, such as by an adjustable, spring-biased diaphragm 730, to open at a fixed relief pressure. The fixed relief pressure may be a value that is a selected fraction of the most recent formation integrity test (FIT) pressure, or "leakoff test" pressure. Such pressure, as is known in the art, is the fluid pressure to which the deepest casing shoe in the borehole, above the "open hole" or uncased portion of the borehole, is tested by pumping drilling fluid into the borehole. Once the fluid pressure acting on the pressure relief valve 728 reaches the preselected fraction of the FIT pressure, the pressure relief valve 728 will open, allowing drilling fluid in the annular space 714 to leave the borehole and return to the mud tank 700. The preselected fraction may be any value deemed to be within industry accepted safety standards, such as 80 to 90 percent of the FIT pressure.

[0095] FIG. 12 shows an alternative embodiment of a safety system that includes a separate, stand alone programmable logic controller (PLC) 724A, referred to as a "safety system" PLC. The safety system PLC 724A may be the same or different type of PLC as the PLC (724 in FIG. 11) used to operate the DAPC. The safety system PLC 724A may be coupled at respective signal inputs to the same or a different pressure sensor 706A and flow sensor 708A as for the DAPC PLC (724 in FIG. 11). In the present embodiment, the safety system PLC 724A may directly operate the shutoff valve 722 in the manner described above with reference to FIG. 11. In some embodiments, the safety system PLC 724A may operate the pressure relief valve 728 rather than having the pressure relief valve 728 be a mechanically operated device.

[0096] In some embodiments, the safety system PLC 724A may be programmed to include essentially the same functionality as the PLC programmed to operate the DAPC system as explained above. In such embodiments, the safety system PLC 724A may be programmed to operate a crossover valve 722A coupled at one outlet thereof to a controllable orifice choke 726A, similar to the valve and controllable orifice choke explained above with reference to FIG. 11. In such embodiments, failure of the DAPC system will

not require stopping of the drilling operation, as the functionality provided by the safety system PLC 724A, its associated sensors 706A, 708A, and controllable orifice choke 726A can provide completely redundant annular space pressure control to the DAPC system.

[0097] While the invention has been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

What is claimed is:

1. A method for controlling formation pressure during the drilling of a borehole through a subterranean formation, comprising:

selectively pumping a drilling fluid through a drill string extended into a borehole, out a drill bit at the bottom end of the drill string, and into an annular space between drill string and the borehole;

discharging the drilling fluid to a reservoir to clean the drilling fluid for reuse;

selectively increasing annular space fluid pressure to maintain a selected fluid pressure proximate the bottom of the borehole by applying fluid pressure to the annular space, the selective increasing including controlling an aperture of an orifice operatively coupled between the annular space and the reservoir; and

discharging fluid from the annular space other than through the orifice when the annular space fluid pressure exceeds a selected value or drops below a selected value.

2. The method of claim 1 wherein the discharging comprises opening a pressure relief valve when the fluid pressure in the annular space exceeds a preselected fraction of a formation integrity test pressure.

3. The method of claim 2 wherein the preselected fraction is between about 80 to 90 percent of the formation integrity test pressure.

4. The method of claim 1 further comprising operating a safety valve if the fluid pressure in the annular space falls below a selected value.

5. The method of claim 4 wherein the operating the safety valve comprises stopping fluid flow to the orifice.

6. The method of claim 4 wherein the operating the safety valve comprises diverting fluid flow from the orifice to a backup selectively controllable orifice.

7. A method for controlling formation pressure during the drilling of a borehole through a subterranean formation, comprising:

selectively pumping a drilling fluid through a drill string extended into a borehole, out a drill bit at the bottom end of the drill string, and into an annular space between drill string and the borehole;

discharging the drilling fluid to a reservoir to clean the drilling fluid for reuse;

selectively increasing annular space fluid pressure to maintain a selected fluid pressure proximate the bottom of the borehole by applying fluid pressure to the annular space, the selective increasing including controlling an aperture of an orifice operatively coupled between the annular space and the reservoir; and

operating a safety valve if the fluid pressure in the annular space falls below a selected value.

8. The method of claim 7 wherein the operating the safety valve comprises stopping fluid flow to the orifice.

9. The method of claim 7 wherein the operating the safety valve comprises diverting fluid flow from the orifice to a backup selectively controllable orifice.

10. The method of claim 7 further comprising causing fluid to flow other than through the orifice if the fluid pressure in the annular space increases above a selected value.

11. The method of claim 10 wherein the causing fluid flow comprises opening a pressure relief valve.

12. The method of claim 11 wherein the pressure relief valve is caused to operate when the fluid pressure reaches a preselected fraction of a formation integrity test pressure.

13. The method of claim 12 wherein the preselected fraction is between about 80 to 90 percent of the formation integrity test pressure.

* * * * *