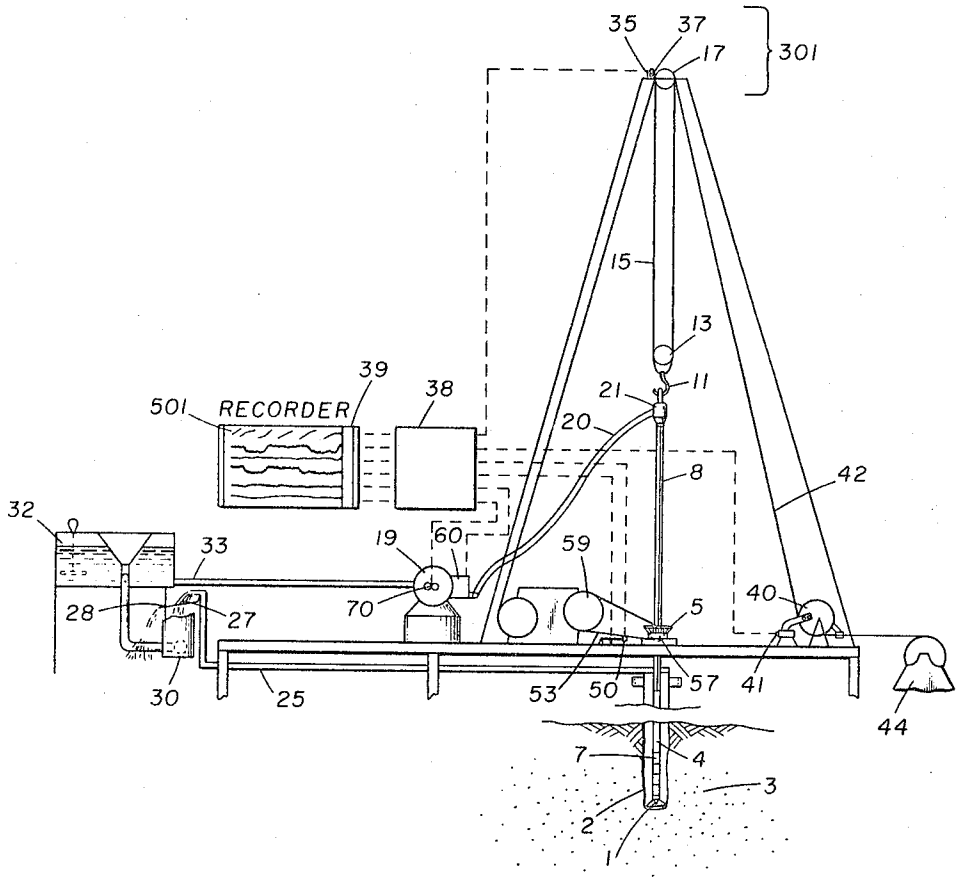
175-48 CROSS REFERENCE SEARCH ROOM

June 13, 1967 W. B. BROOKS ETAL 3,324,717

SYSTEM AND METHOD FOR OPTIMIZING DRILLING OPERATIONS

Filed Oct. 28, 1963 6 Sheets-Sheet 1

FIG. 1

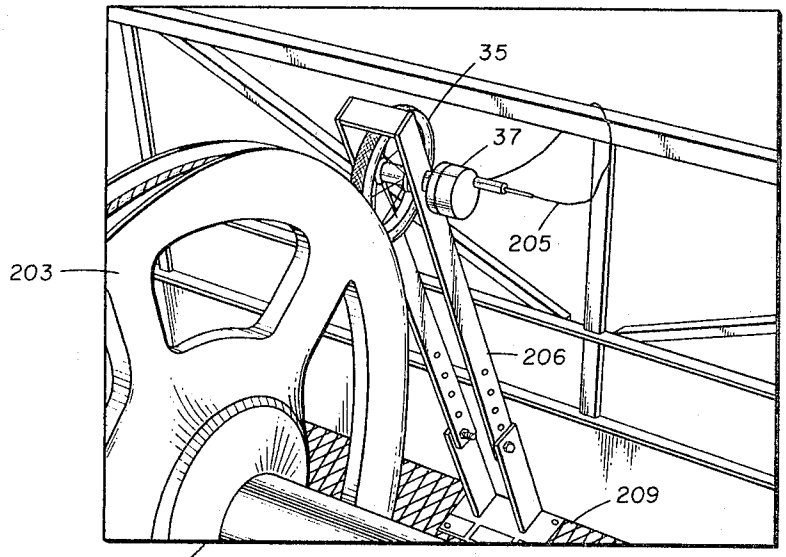


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FIG. 2



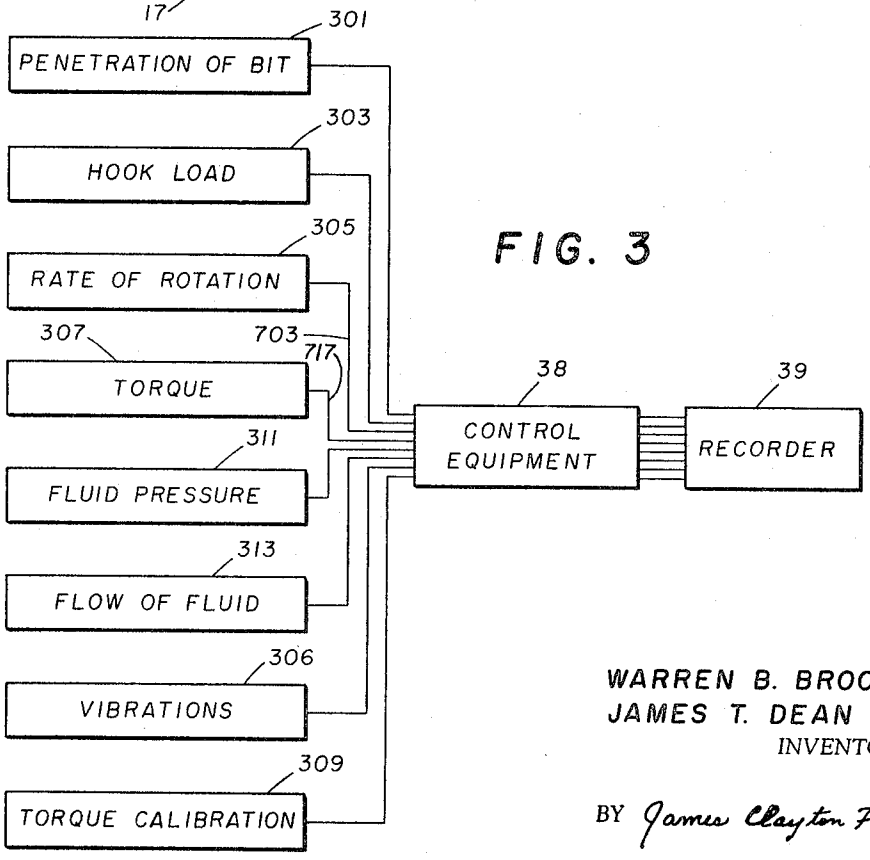


FIG. 3

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SYSTEM AND METHOD FOR OPTIMIZING DRILLING OPERATIONS

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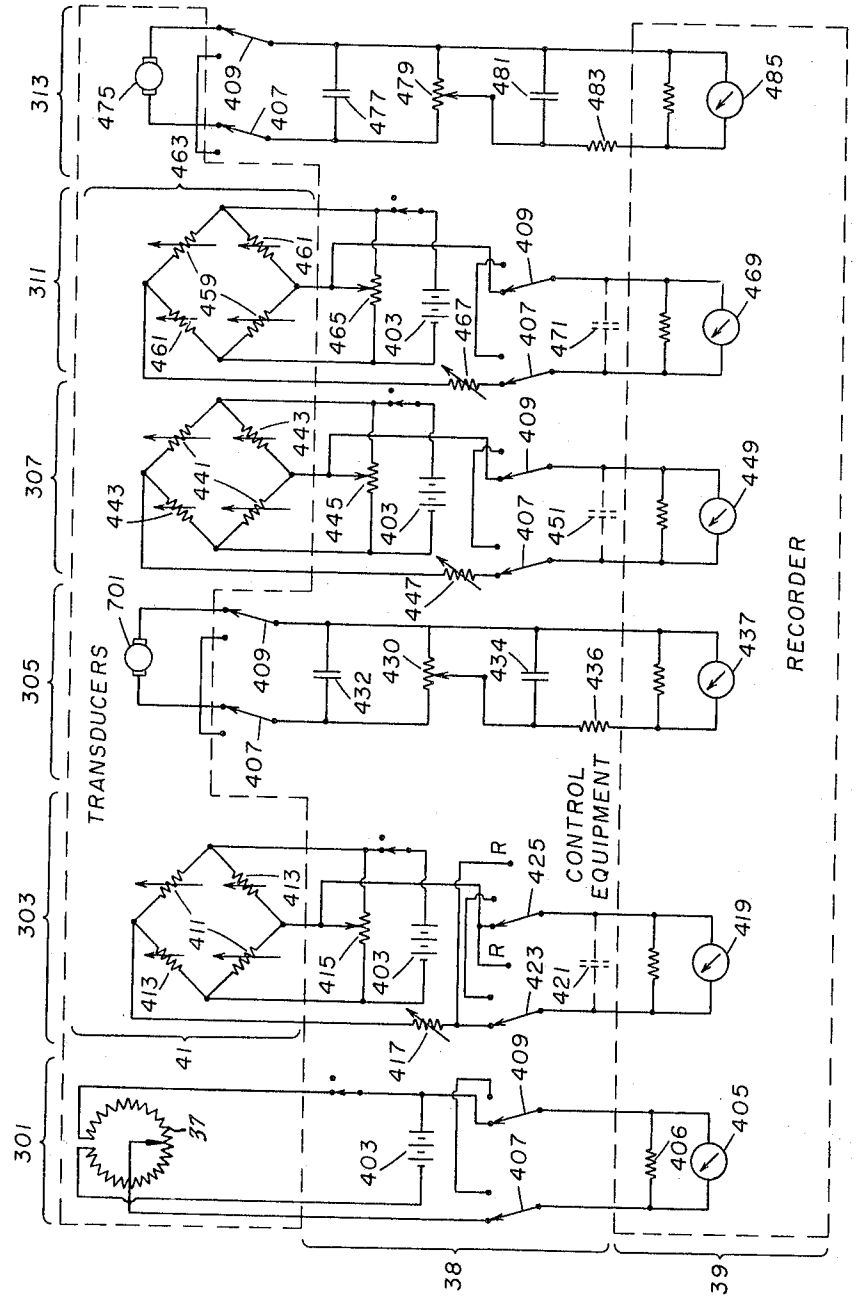


FIG. 4

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SYSTEM AND METHOD FOR OPTIMIZING DRILLING OPERATIONS

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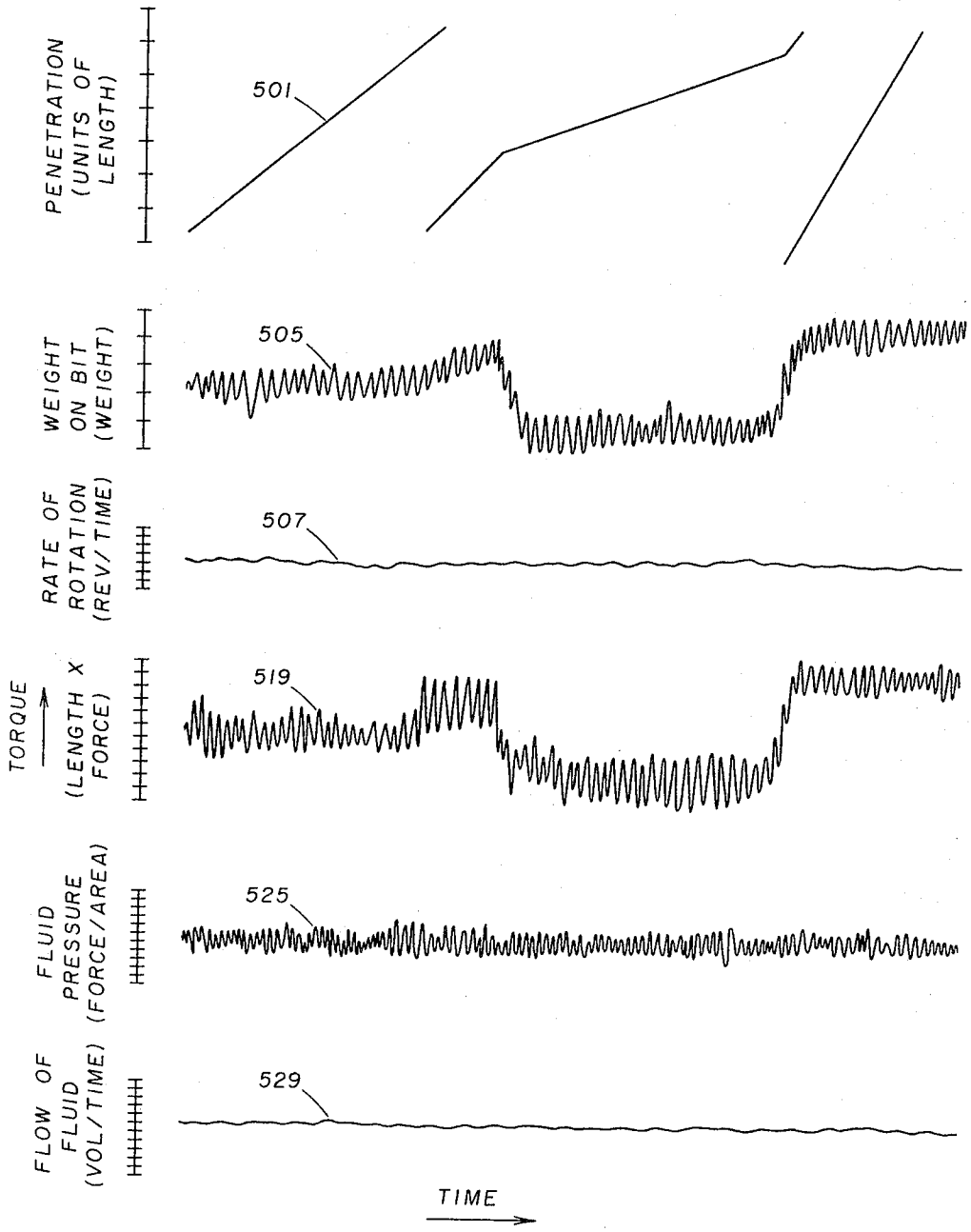


FIG. 5

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SYSTEM AND METHOD FOR OPTIMIZING DRILLING OPERATIONS

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FIG. 6

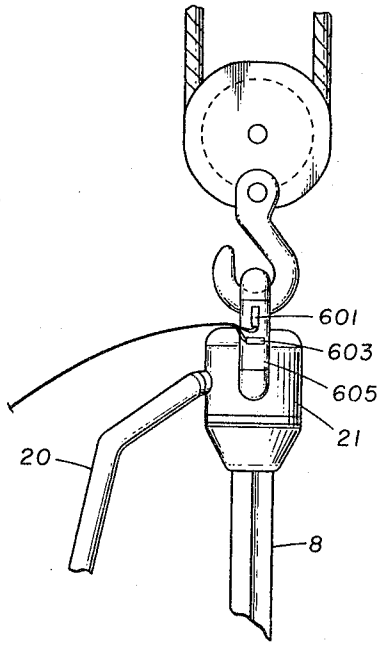
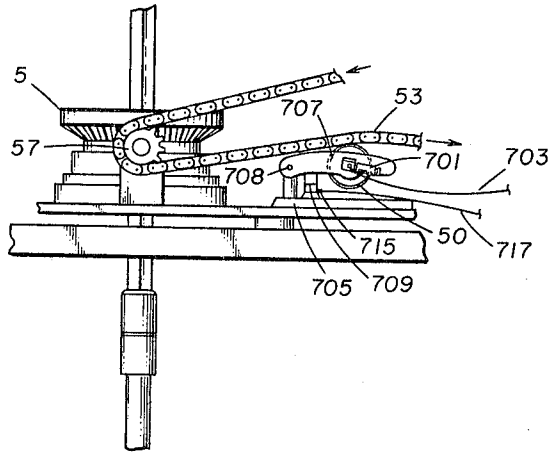


FIG. 7



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SYSTEM AND METHOD FOR OPTIMIZING DRILLING OPERATIONS

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FIG. 9

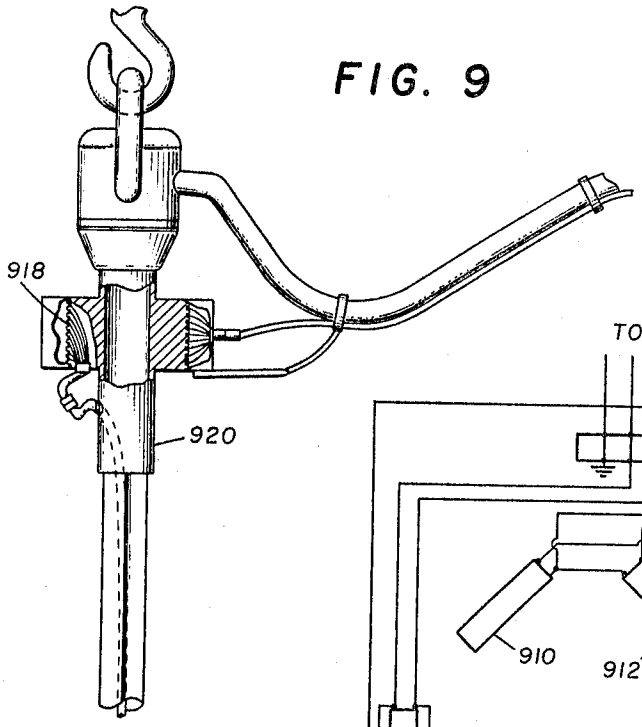
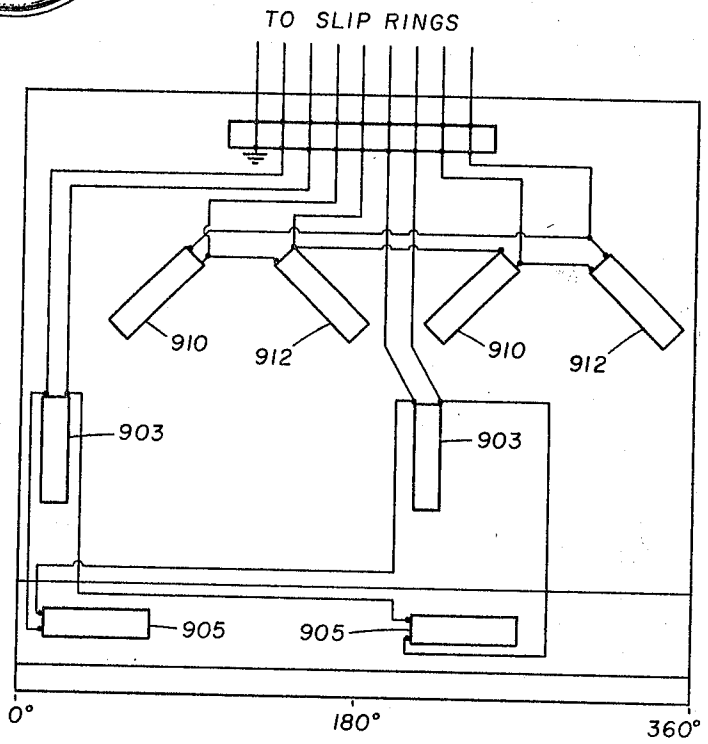
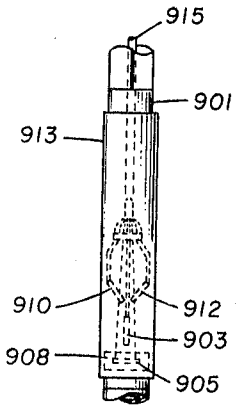


FIG. 10





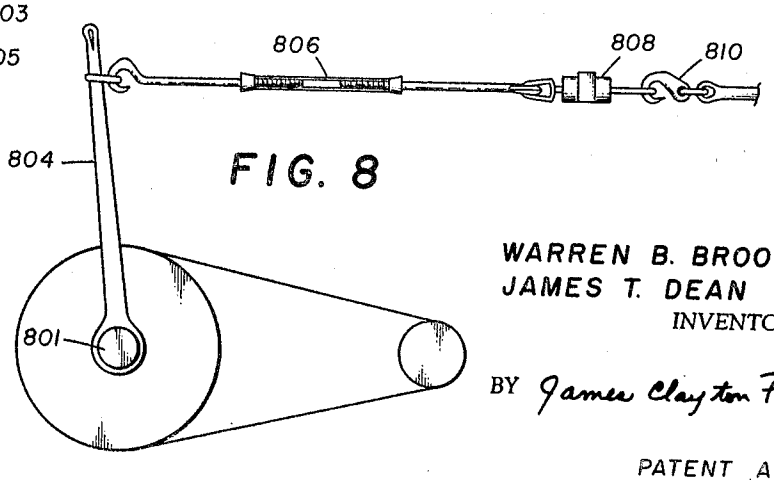


FIG. 8

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United States Patent Office 3,324,717
Patented June 13, 1967

3,324,717

SYSTEM AND METHOD FOR OPTIMIZING DRILLING OPERATIONS

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Filed Oct. 28, 1963, Ser. No. 319,287
11 Claims. (Cl. 73—152)

This invention relates to a system for use in drilling operations. Specifically, it relates to an improvement in instrumentation and methods employing same, used in drilling boreholes into subsurface formations. More particularly, it relates to an improved drilling information gathering system which will afford at least the minimum information necessary for thorough monitoring, recording, analyzing, and controlling the rotary drilling operation and its multiple and interrelated variables. It also relates to improved methods using this improved drilling information gathering system.

The earliest oil wells were drilled with crude digging apparatus. Then came cable tool rigs. As the wells were drilled deeper, rotary drilling rigs came into being. In rotary drilling, a power rotating means delivers torque to a drill string, sometimes referred to as a drill stem, which turns a bit drilling the borehole into the subsurface formations. Since bailing, or manual removal of cuttings, is prohibitive at depth, a drilling fluid is circulated to clean the bit and bottom of the borehole, bringing the rock cuttings to the surface. From the inception of rotary drilling, many improvements have been made. Especially in recent years there has been a determined and scientific approach to recording and analyzing drilling operations. We have been engaged for many years in trying to improve drilling operations. This necessitates on-the-spot monitoring, analysis, and control; as well as subsequent comparison of the various drilling records to evaluate improvements in drilling techniques. Despite the significant achievements by others in this field, there was no system available which would allow correlative recording of the minimum variables we found necessary to fulfill these objectives. By correlative recording, we mean recording in a manner such that the particular and respective values of the variables producing the observed result were preserved in certain, correlatable form.

To get a complete picture of the efficiency of a drilling operation, it is necessary to know the value of at least six variables:

(1) drilling rate or penetration with respect to time;
(2) weight on the bit;
(3) rate of rotation of the drill string;
(4) torque imparted to the drill string, often referred to simply as torque;
(5) pressure of the drilling fluid; and
(6) flow, or circulation rate, of the drilling fluid.

It is also necessary to monitor or know the value of vibrations being transmitted up the drill string when a bit employing vibratory energy is being used. We have found monitoring vibrations to be very useful in optimizing rotary drilling operations. Others have developed systems for independently recording one or more of these variables, but have not recorded simultaneously all six or seven variables before our invention. Particularly, they have not recorded at least these variables onto a unitary record. Most of these system suffer from the adverse effects of temperature change, pressure leakage, humidity difficulties, spurious high frequency signals, etc. Moreover, the variables were recorded on multiple records, so obtaining correlative values was somewhat difficult and uncertain.

Accordingly, it is an object of this invention to provide a superior drilling information gathering system. It is an object to provide a method of improving the drilling operation. It is also an object of this invention to provide a drilling information gathering system whose output record affords at least the minimum data necessary for a complete engineering analysis of the drilling operation. A further object is to provide a drilling information gathering system and record free of distortion, inaccuracies, and difficulties due to excessive temperature or humidity.

It is a further object to provide a system for gathering and recording information in a rotary drilling operation. It is also a further object to delineate a method of using the drilling information gathered to control the drilling variables to improve the drilling operation.

It is a still further object to provide improved elements in the data information gathering system. It is particularly an object to provide an improved torque measuring element. It is thus an indirect object to prevent "twistoffs" and other common difficulties due to inaccurate torque measurement brought about by temperature changes or fluid leaks. It is also a particular object to provide an improved drilling rate detector.

It is also an object of the invention to provide an accurate log of the nature of subsurface formations being penetrated. It is also an object to distinguish between apparent but unreal "hard" formations by simultaneously and correlatively recording all variables. It is also an object to delineate the degree of wear of the bit teeth, or bit bearing, or both. It is also a further object to predict and prevent the occurrence of major difficuluties in drilling.

These and further objects will become apparent as the description of the invention proceeds. The scope of these objects is limited only by the appended claims.

FIGURE 1 is a schematic of a rotary drilling rig, showing one embodiment of our invention;

FIGURE 2 is a sketch of the wheel and potentiometer mounted in juxtaposition the fast sheave as one means for generating a function representative of penetration of the bit into the formation;

FIGURE 3 is a block diagram showing the various drilling information which has been gathered, fed through the control equipment, and recorded in the manner of the invention;

FIGURE 4 shows a schematic of an illustration circuit for producing a unitary record of the drilling variables;

FIGURE 5 shows a typical section of a "normal" unitary record produced by the drilling information gathered;

FIGURE 6 is a sketch showing strain gauges installed on the bail of the swivel as an alternate embodiment for obtaining hook load which can be converted by instrument and control circuit modifications to weight on the bit;

FIGURE 7 is a sketch showing the primary embodiment for measuring torque and rate of rotation imparted to the drill string;

FIGURE 8 is a sketch showing the apparatus used in calibrating the torque measuring device of FIGURE 7 to read in absolute units of torque;

FIGURE 9 shows schematically the insertion of a specially instrumented "sub" into the drill string as an alternate embodiment for measuring torque, vibrations, and weight on the bit; and

FIGURE 10 shows a schematic, obtained by unfolding or flattening the "sub's" exterior, of the standard Wheatstone bridge circuitry used in connecting the strain gauges on the "sub" used as an alternate embodiment for analyzing drilling operations.

Broadly stated, our invention lies in the combination, or system, for gathering at least the minimum necessary amount of drilling information into a unitary, time-saving record where correlative values of the respective variables can be determined accurately and with certainty. Some of the elements of the combination are themselves improvements we have found necessary for the simple, rugged, dependable service demanded in the field. For example, the instrumentation is accomplished without using less durable components such as amplifiers. Such improved instrumentation and records will almost always engender improved methods for analyzing and controlling the complex and interrelated variables of the drilling operation. From such improved methods we have selected and claimed those which appear most useful and novel.

Our system affords a unitary, easily interpretable, accurate record regardless of the speed at which the recorder is run, e.g. from the one foot per hour to as fast as two feet per second. In the past, even when more than one drilling variable was recorded, differing records were obtained. Getting correlative values of the variables was difficult and uncertain with such separate recording. This is one of the particular advantages of our system.

More specifically, our invention concerns a drilling information gathering system for optimizing drilling by a drilling rig wherein a power rotating means delivers torque to rotate a drill string turning a bit drilling a borehole through subsurface formations, while simultaneously circulating drilling fluid to keep the bit and the bottom of the borehole cleaned of cuttings. The system has means for detecting and generating a function representative of (1) penetration of the bit into the subsurface horizon, (2) weight on the bit, (3) rate of rotation of the drill string, (4) torque imparted to the drill string, (5) pressure of the drilling fluid, and (6) flow of the drilling fluid. Coupled to these function-generating means and responsive thereto is a single recorder for simultaneously and correlatively recording with respect to an independent variable, such as time, at least the above-mentioned six variables to afford data for meaningful technical analysis and control.

In drilling operations off Gabon, Africa, our drilling information gathering system was used, replacing diverse, less accurate, less complete instrumentation. Significant savings resulted from the improved control by the same drilling engineer, who now had a complete story of the drilling operation in analyzable form. In that test the need for a housing and temperature and humidity control was emphasized.

Further inquiry into the complex and interrelated variables of the drilling operation reinforces the conclusion that only a drilling information gathering system will suffice. This becomes especially true in the forthcoming automation of the drilling operation.

Having these drilling variables recorded simultaneously and correlatably, and especially on a unitary record, facilitates exploiting their interrelationships in methods of improving the drilling operation. A somewhat qualitative discussion of the interrelationship of these variables and how they can be used to improve the drilling operation will illustrate this point.

The drilling rate, that is, the slope of the curve of penetration versus time, is important for several reasons.

First, it affords a measure of the "hardness" of the formation, thus giving the geologist a "log" of the well. But it does this directly only if the weight on the bit remains constant; if the rate of rotation remains the same, at relatively the same torque; if the bit does not grow dull; and if the pressure and flow of the drilling fluid are adequate to clean the bit and bottom of the borehole and indicate trouble-free operation. Thus, these must be simultaneously monitored and the "log" appropriately corrected. A sensitive monitor of penetration versus time is needed to detect very small "drilling breaks" and thus provide an accurate "log" of the lithology of the subsurface formations.

Second, the drilling rate is a direct measure of the efficiency and efficacy of the drilling operation or innovation being used. But this is so only as long as (1) the weight on the bit is maintained, (2) the rate of rotation remains at the desired setting, (3) the torque remains approximately constant, (4) the bit remains sharp, (5) the pressure of the drilling fluid remains substantially normal, and (6) the flow of the circulation drilling fluid remains adequate to clean the bit and the bottom of the borehole and indicate trouble-free operation. These variables must be monitored and controlled during the drilling operation. Where variations exist, corrections for the effect must be made on subsequent analysis.

Third, the drilling rate affords an excellent way to optimize the drilling operation for the formation being drilled. For example, the weight on the bit can be varied while the other variables are held reasonably constant and the effect of the variation noted on the change of drilling rate. This is simply the change in slope of the plot of penetration versus time. Similarly, the rate of rotation of the drill string can be varied and its effect noted while the other variables are held substantially constant.

In the same way, the flow of the drilling fluid can be varied and its effect noted. These three: weight on the bit, rate of rotation of the drill string, and flow of the drilling fluid are generally conceded to be the independent drilling variables. That is, they can be completely controlled within equipment limitations to optimize drilling operations. Infrequently, independent control is exercised or attempted over other variables. For example, vibrations have been impressed onto the drill string from an independent external source.

These independent variables can be manipulated individually, separately, or sequentially to achieve the optimum combination. That is, only one of the variables may need to be changed if drilling in fairly familiar environments where very little change is necessary to optimize the drilling variable taught by past experience or previously recorded optimum drilling variables. Manipulating more than one variable will be required when drilling in more unfamiliar environments. In rank "wildcats," each of the drilling variables will have to be varied to determine the optimum combination. Once determined, the drilling variables so optimized are correlated with the formation being drilled as indicated by the "log" of the lithology of the subsurface formations, the geological samples, and the torque record, or by other logs. The drilling variables so optimized are then recorded on permanent, retrievable records as a function of locale, depth, and specific or type formations. These records facilitate subsequent optimization of similar drilling operations.

These drilling variables can be varied or changed intuitively or empirically by a skilled drilling engineer. To achieve the optimum and most nearly universal usefulness, however it is better to start with the drilling variables at moderate or low values and increase in predetermined increments, preferably equal. This gives a good set of normal operating values, or norms, for the other or dependent drilling variables; that is, penetration of the bit, torque, pressure of the drilling fluid, and vibrations when recorded. The relative effectiveness of the incremental changes is thus determined by the record. If low or moderate values are used for the independent drilling variables, the equal incremental increases, i.e. the increments, should be continued until the one produces, or causes, an increase in the drilling rate less than the increase produced, or caused, by the preceding increase. It may continue until the increase of drilling rate is down to seventy percent to that of the preceding increase.

Where the increments are unequal, the varying should continue until the increase of the drilling rate per unit of variation lies somewhere between seventy and one hundred percent of that produced by the preceding increase.

When the increase of drilling rate shown by the record to be caused by a particular increment in less than half that of a previous equal increment it is almost certainly uneconomical and hence not optimal. Because of the complicated interrelationships, more empirical information will be necessary to more accurately define the limitations. The torque record affords a good source for this empirical information. For example, if the wear on the bit for a given weight was indicated by the torque to be about the same as that for a previous value of the weight on the bit, the new value might be economical even though it caused only sixty percent as much increase as the preceding change.

It is immediately apparent that varying an independent drilling variable may vary a dependent drilling variable. That is, it will establish a coordinated norm, or new normal operating condition, for the dependent variable. For example, the pressure of the drilling fluid must be increased to increase the flow of the drilling fluid; also, increasing the weight on the bit increases torque. These coordinated norms are, of course, used in monitoring the other dependent drilling variables for any uncordinated departure that would invalidate the optimizing procedure. If any such departure is observed, the optimizing is stopped until the departing variable is restored to normalcy, that is, to its norm or coordinated norm. Thereafter, the optimizing procedure is continued.

While we have not experienced any such condition, it is conceivable that the initial values of one or more of the independent drilling variables could be too high. In such a case, that is, if the initial increase caused no increase in the drilling rate, this drilling variable could be decreased either empirically or in increments, preferably in increments, until it caused a decrease in drilling rate, or rate of penetration. It could then be increased to restore the initial rate of penetration. If such a situation is encountered, the drilling engineer can simply back off to a lower value and optimize by increasing the variable as outlined above.

Thus, an optimum combination can be realized for a given type formation. The type formation can be identified as indicated above as well as by high frequency components of the torque and weight on the bit functions. For example, a hard rock formation will cause more of these high frequency components of generally higher amplitude. This optimum is only good for a particular degree of wear of the bit, which can be estimated from the torque as discussed below. Further no optimum can ever be realized if inadequate fluid horsepower is being developed to clean the bit and bottom of the borehole. With such inadequate fluid horsepower, increasing the pressure and flow of the fluid being circulated dramatically increases the drilling rate at given weights on the bit and given rates of rotation. But these large increases continue only up to the point where the cones are kept clean, "balling" of the bit is prevented, and the bottom of the borehole is kept clean of cuttings, thus preventing regrinding of previously drilled material with all the wasted energy thereby entailed. Thereafter, except under certain conditions, the increases may be too small to warrant the cost of developing higher fluid horsepower. Our invention is useful in delineating these conditions. The optimum drilling fluid circulation rate and pressure can be determined by and thereafter accurately controlled using this drilling information gathering system. And, of course, such a system is most useful in warning of impending difficulties. For example, a sudden increase in pressure and decrease in flow will warn of partial plugging of the bit. This will allow unplugging and prevent subsequent "twistoff" and "sticking in the hole."

Fourth, the drilling rate monitor system allows accurate control of the speed of pipe being run in or out of the hole. This of course controls pressure surges to minimize dangers of cave-ins.

Equally as useful as a diagnostic tool is the torque measuring device. For example, increasing torque indicates wear on the bit bearings. A sudden sustained increase in torque can be indicative of a locked cone on the bit. Pulling the bit at this time prevents a dropped cone and the very expensive fishing operation attendant therewith. But it only indicates this if other operating conditions at this instant, that is, the correlative values of weight on bit, rate of rotation, drilling rate, and pressure and flow of the drilling fluid, are constant or known. Higher weight on the bit will cause an increase in torque, as will higher rotation rate in the same formation. A change in character of the subsurface formation, which can be detected by a change in the rate of penetration, will cause fluctuations of torque. A sudden increase of pressure and decrease of flow of the drilling fluid can warn of cave-ins which can increase the torque. Torque is also useful in other respects. It can depict by oscillations drill string whip with its loss of energy. It can delineate hard fractured zones by high-amplitude, high-frequency spikes illustrated on a recording graph. It is a natural measure of the wear of the bit. That is, as the bit gets dull there is a gradual decrease in torque while the other values of the drilling variables remain reasonably constant. The drilling rate decreases concomitantly with this lowering of torque as the bit teeth become worn. When the bit gets very dull or out of gauge, there is a fairly rapid decrease in torque. When the bit is thus indicated to be dull, it can be checked by increasing the weight on the bit. If there is inadequate increase, i.e. below previously determined increase ranges in torque and rate of penetration, the bit should be changed. Thus the bit can be changed at an optimum time; neither too "green" and thus inefficient, nor too late, e.g., when a cone is dropped, and thus expensive. The usefulness of the torque measuring device was foretold by Messrs. E. L. Decker and F. S. Crane, "What's New in Drilling Instruments," The Oil and Gas Journal, Nov. 29, 1954. We have found the basic Martin-Decker torque measuring unit an excellent, rugged device on which to graft improvements yielding better accuracy and stability.

A detailed explanation of the invention follows. The description is given primarily with respect to rotary drilling operations where the invention achieves its most immediate application. However, the invention is very flexible. It is useful in any drilling operation wherein a power rotating means delivers torque to rotate a drill string turning a bit drilling a borehole into subsurface formations while circulating a drilling fluid to keep the bit and bottom of the borehole cleaned of cuttings.

Referring now to FIGURE 1, in a conventional rotary drilling operation a bit **1** is used to drill a borehole **2** into subsurface formations **3**. The bit is rotated by a drill string **4**, often called a drill stem. The drill string **4** is in turn rotated by some power rotating means such as a rotary table or turntable **5**. A compressive force is impressed onto bit **1** to cause it to penetrate subsurface formations **3**. Accomplishing this will be drill collars **7** making up the lower portion of the drill string **4**. Technically, the rotary table **5** does not impart torque directly to the drill string **4** but to a kelly **8**, which is normally a square or hexagonal member which translates the torque to the drill string **4**. For simplicity, this is spoken of as transmitting torque to the drill string and will be used hereafter in this fashion. Generally, the drill pipe is held in tension and only the weight of the drill collars allowed on the bit, hence a portion of the load must be borne by a hook **11** attached to a traveling block **13**. This traveling block **13** is moved by multiple windings of cable **15** over a crown block **17**. To achieve less or more weight on the bit, the traveling block **13** is raised or lowered to take more or less of the weight of the drill string. Simultaneously with the rotation of the bit under a compressive force, a drilling fluid is circulated by a drilling fluid pump **19** through a conduit **20** into a swivel **21** and hence through the kelly **8** into the drill string **4**. This drilling fluid keeps the bit teeth clean,

prevents "balling" of the bit, washes the cuttings from the borehole, and returns these cuttings to the surface. Where a drilling mud is used as the circulating drilling fluid, a return conduit 25 conveys these cuttings 27 onto a screen 28 for analysis by the geologist. This is very valuable aid in correlating the lithology being penetrated with the drilling variables observed as hereinabove discussed. Drilling mud then falls into a sump 30 and thence is moved by way of a pump (not shown) to a recirculating or stowage vat 32. Therefrom a suction line 33 goes to the drilling fluid circulating pump 19. Where air or gas is used as the drilling fluid, such recirculation conduits and vessels are not necessary. While air and gas achieve substantially increased rates of penetration of the borehole in a subsurface formation, they have the disadvantage of making the recovery of geological samples difficult. The difficulty involved in obtaining geological samples in air or gas drilling increases the value of a sensitive monitor of penetration versus time for correlation with the lithology log of the subsurface formations. The drilling information gathering system will also monitor the pressure and flow, or circulation rate, of air or gas when these media are used as the drilling fluids.

Our invention lies in instrumenting the briefly described rotary drilling rig to allow us to control the variables and optimize the drilling which can be achieved. As a means for generating a first function representative of penetration of the bit into the subsurface formation, we attach a wheel 35 (FIGURES 1 and 2), preferably having a rubber tire thereabout, in juxtaposition one of the sheaves of the crown block 17 for controllable proportioning movement and trouble-free operation. A potentiometer 37 having a constant voltage, direct current (D.C.) power supply (not shown) is keyed to the shaft of this wheel 35 and thus produces a voltage that is proportional to movement thereof. By locating the wheel 35 in juxtaposition the proper sheave of the crown block 17 and adjusting the size of the wheel, it is possible to achieve a direct correlation of the movement of the wheel 35 to a unit of depth drilled by the bit 1. For example, assuming a five-sheave crown block and a four-sheave traveling block are in use with the drilling cable traversing the perimeter of each sheave, if the perimeter of wheel 35 is two feet, each revolution of the wheel and hence each traverse of the potentiometer and the voltage function thus generated, represent a one-foot penetration of the bit when located in juxtaposition the second sheave on the crown block where the deadline sheave is the first sheave. When moved to be in juxtaposition the fifth sheave, or the fast sheave 203 as illustrated by FIGURE 2, each revolution only represents a penetration of one-fourth foot. Thus, extremely accurate monitoring of penetration can be achieved by this method. As shown, the output from the potentiometer 37 is fed to control equipment 38 and thence to a recorder 39 which records this penetration on a record being advanced in accord with advancing time. In this manner, the slope of the record thus achieved represents the rate of penetration, often called drilling rate; that is, the plot of penetration versus time. With this type recording, it is possible to sense a movement of the kelly to an accuracy of one-eighth inch and to monitor drilling breaks of the same magnitude.

FIGURE 2 shows a close-up of the above-described means for generating the function representative of penetration of the bit in the formation. Therein a wheel 35 is in contact with the fast sheave 203 of the crown block 17. Potentiometer 37 is connected with the wheel 35 and by cables 205 to control equipment 38 and hence to recorder 39 (FIGURES 1 and 3). The entire assembly is supported by any suitable bracket means 206 fastened to the crown block support 209. As can be seen in FIGURE 3, the output from the means for generating a function representative of the penetration of the bit, shown as block 301, is then fed to the control equipment and hence to the recorder. The circuit diagram can

be seen in FIGURE 4. Therein, the portion of the electrical circuit corresponding to the block 301 of the block diagram of FIGURE 3, and indicated by the same indicia, shows the potentiometer 37, which serves as the transducer, powered by a constant voltage D.C. power supply shown as battery 403 in the control equipment 38. Thus the output of the potentiometer 37 generates a function, voltage, representative of the penetration of the bit into the subsurface formations. This function causes a deflection of galvanometer 405 in recorder 39, if the control switches 407 and 409 are on, to plot penetration versus time as shown by plot 501 in FIGURE 5 and FIGURE 1. A damping resistor or shunt 406 is typical of one each used with, but not hereafter described in connection with, each galvanometer in the system. Such damping is unnecessary on a fluid damped type galvanometer. While FIGURE 2 shows the wheel 35 in juxtaposition the fast sheave 203 of the crown block, it will be readily apparent that it can be positioned in juxtaposition any sheave, depending on the rate of drilling. For example, we have found that during "coming out of the hole" operations, the wheel 35 turns too rapidly if it is located on the fast sheave. For simple, trouble-free operation, we have used a 360° single turn, continuously rotatable potentiometer 37, and have replaced the metallic resistive wire element of the potentiometer with resistive plastic. The potentiometer 37, when generating the first function, accurately represents small and large movements of the bit with respect to time.

As a means for generating a second function representative of hook load, or modified to represent weight on the bit, we use the following instrumentation. To measure the weight on the bit, we connect to a deadline diaphragm unit 40 (FIGURE 1) a strain gauge type pressure transducer 41. The reason for this choice is simplicity of installation. The deadline diaphragm unit 40 is usually in existence on the drilling rig. It is simply an eccentrically mounted spool around which the cable 42 is wound. A storage drum 44 generally has spare cable so that when the cable becomes worn it is only necessary to feed it through the various sheaves in the crown block 17 and traveling block 13. This is more economical than rethreading. Hence, to instrument any particular rig is a simple matter. Conventionally, a deadline diaphragm unit 40 will be used with a remote indicating pressure gauge on its hydraulic system. We have found that we can connect a pressure transducer 41 directly to the deadline diaphragm unit 40 and incur very little error in our measurement.

Referring to FIGURE 3, the output from the means for generating a function representative of the hook load, shown as block 303, is sent to control equipment 38 and thence to recorder 39. In the circuit diagram of FIGURE 4, the portion of the electrical circuit corresponding to the block 303 of FIGURE 3, and indicated by the same indicia, has the hook load being measured by active strain gauges 411 in pressure transducer 41. Dummy or passive strain gauges 413 provide temperature compensation. Active strain gauges 411 are arranged to be responsive to both temperature and strain induced by the pressure. Dummy strain gauges 413 are arranged to be responsive only to the temperature. Strain gauges 411 and 413 are connected alternately each to the other as shown and form the elements of a Wheatstone bridge. The Wheatstone bridge is balanced by potentiometer 415 and powered by battery or constant voltage D.C. source 403. Range of the hook load monitor is changed by rheostat 417. Change in hook load then causes a deflection of galvanometer 419. While the hook load can be recorded directly for the greatest amount of information, we often found it helpful to install a filter, shown as dotted capacitor 421, to remove high frequency components from the recorded function generated. This is more particularly true when using one of the alternate embodiments described below.

For extreme stability, we completely remove the hydraulic unit and replace it with a BLH load cell which is automatically temperature compensated. The connections and principle of operation remain the same except the active strain gauges **411** measure strain in a solid compressive member.

As instrumented, the measurement will be of the weight of the hook load on the traveling block. This can be recorded per se. However, this generally involves further manipulation either manually or by controller to determine the amount and direction in which to correct. For example, in FIGURE 5, it is much more convenient to have the curve **505** read directly the weight weight on the bit than to have it reading hook load, in which case corrections have to be made as the weight of the drill string increases. This can be done by reversing the wiring of the instrument. This is accomplished by moving control switches **423** and **425** to position R for the reversal. The maximum hook load then becomes an artificial zero point. As weight is sustained by the bit, the hook load will decrease. In this manner, the instrumentation and control equipment, since its wiring has been reversed, generate a function representative of weight on the bit by measuring the decrease of the hook load as a measure of the weight on the bit. Since the maximum hook load will change with each stand of drill pipe used, essentially a recalibration is done with each stand of drill pipe added to the drill string. Thus, the use of a diaphragm unit in the deadline poses no major problems of temperature instability when the instrumentation of the invention is used.

An alternate embodiment can be seen in FIGURE 6. This embodiment is preferred where a drilling program will last long enough to justify the instrumentation installation. This embodiment is particularly preferred when it is desired to obtain information from the vibrations, or high frequency components of the signal. That is, strain gauges **601** and temperature compensating strain gauges **603** are installed on the bail **605** of a swivel **21**. As before, the drilling fluid will circulate through the conduit **20** and down through the kelly **8** into the drill string (not shown).

The active strain gauges **601** are used in the same circuits **303** of FIGURE 4 as are active strain gauges **411** of pressure transducer **41**. Similarly, the "dummy" strain gauges **603** are used as are dummy strain gauges **413** to afford temperature compensation. This method affords an excellent, stable, sensitive way to monitor indirectly the weight on the bit by monitoring the hook load. As taught above, control equipment **38** can be manipulated to generate a function representative of weight on the bit.

This embodiment can also be used to generate and record a function representative of vibrations and is shown as block **306** (FIGURE 3). Expressed generally, the means for generating a seventh function representing vibration in the drill string incorporates a strain gauge and a power source, the strain gague being connected in an electrical circuit with the power source and physically attached to a member integrally movable with, and bearing part of the weight of, the drill string whereby the strain gauge modifies the electrical signal from the power source in response to changes of tension in the member. Vibrations are helpful in controlling and analyzing even rotary drilling. They are essential in some instances. Optimum traces of vibrations are produced when they occur as cyclic high amplitude signals in the shallow portions of a borehole and cyclic low amplitude signals in the deep portions of the boreholes.

The output from either of these instruments, measuring the hook load, goes to the control equipment **38**, where it is corrected to measure weight on the bit. This is then sent to recorder **39** where it is recorded on the record which is being advanced with advancing time. A plot similar to curve **505** in FIGURE 5 can be obtained. Thus, the value of the weight on the bit which produced the particular penetration, plotted on the same advancing record as the penetration, can be observed and used in subsequent comparative tests. It can thus be used to control, manually or automatically, the lowering of the traveling block to achieve and maintain any desired weight on the bit.

As a means of generating a third function representative of the rate of rotation of the drill string, an idler wheel **50** (FIGURE 1) is placed in juxtaposition and responsive to movement of a lineal member **53**. This lineal member **53** connects the turntable **5** through suitable gearing and rotatable member **57** to a prime mover **59**. The lineal member is connected in endless fashion between the prime mover **59** and the rotatable member **57**. By endless fashion is meant such device as a chain or belts between pulleys. By prime mover **59** is mean some power "take-off" point for some primary energy converter such as an electric motor or diesel engine. In this way the rate of rotation, or r.p.m., of the idler wheel **50** is proportional to the rate of rotation, or r.p.m., of the drill string **4**. This idler wheel **50** may be a smooth wheel responsive to the friction movement of the lineal member **53** or it may be a toothed wheel which can be turned more positively by a chain drive from the prime mover **59** to the rotatable member **57**. We have found the smooth idler wheel to be preferable. This can be seen in FIGURE 7. Therein the idler wheel **50** applies a force to cause a slight transverse movement of and responds to the lineal motion of lineal member **53**, and in turn drives a D.C. generator **701**. The D.C. generator **701** generates a function, a voltage, proportional to the rate of rotation, or r.p.m. As shown in FIGURE 3, this output from the means generating a function representative of the rate of rotation, shown as block **305**, i.e., this D.C. voltage function, is sent by cable **703** to the control equipment **38** and hence to the recorder **39**. It is recorded directly as representative of the r.p.m. FIGURE 4 shows the detailed schematic. The D.C. generator **701**, or tachometer **701**, output is sent through potentiometer **430**. Capacitors **432** and **434** improve the quality of the function generated, i.e., the sampled voltage output. This voltage is impressed across resistor **436** and causes galvanometer **437** to deflect. A record similar to curve **507** of FIGURE 5 is produced.

FIGURE 7 also shows the means for generating a fourth function representative of the torque imparted to the drill string. Therein a conventional Martin-Decker torque measuring device **705** is used to support the idler wheel **50** distorting the lineal member delivering power to rotate the rotary table. The Martin-Decker device is commercially available as a HydroMech Unit, from Long Beach, California. It comes equipped with supporting structure of a hydraulic cylinder and hydraulic gauge which can be remotely mounted on the drilling rig. The increasing torque tends to depress a lever arm **707**, of the unit. It is pivoted at point **708** and thus tends to put into compression supporting structure **709** or increase the pressure on any contained hydraulic fluid supporting lever arm **707**. We have simply inserted a standard BLH pressure cell **715**, available from BLH Corporation, Waltham 54, Massachusetts, which monitors the pressure in the hydraulic system. This is connected by cable **717** to control equipment **38** and hence to recorder **39**. This pressure is directly proportional to the torque exerted in the system. For extreme stability, we completely remove the hydraulic supporting structure and replace it with a BLH load cell which is automatically temperature compensated. We have found the standard BLH load cell to be preferable since it can be calibrated to read absolute torque and will continue to do so despite temperature changes. Referring to FIGURE 3, the diagram block **307** designates a means for generating a function representative of torque, which function is fed to control equipment **38** and thence to recorder **39**. The usual balanceable

bridge circuitry and principle is employed. It is very similar to that described above in monitoring the weight on the bit. Both the BLH pressure cell and the BLH load cell monitoring torque employ active strain gauges 441 (FIGURE 4) in Wheatsone bridge confiuration with dummy strain gauges 443 for temperature compensation. The Wheatstone bridge is balanced by potentiometer 445 and powered by a constant voltage source such as a battery 403. Range of the torque monitor is changed by rheostat 447. Change in torque then causes a deflection of galvanometer 449. While the torque can be recorded directly for the greatest amount of information, we have often found it helpful to install a filter, shown as dotted capacitor 451, to remove high frequency components from the recorded function generated. We have found, however, that the high frequency information can be interpreted and give additional meaning to the drilling operation in many instances and have often omitted this capacitor 451. The record produced will vary widely depending on the filtering used. One example is shown as curve 519 in FIGURE 5.

To calibrate the system so that the torque measured is in obsolute value instead of a relative one, a measured torque is developed on a shaft somewhere in the power transmission system and recorded concurrently with the output of the torque transducer. Measured torque is developed by placing a wrench with a measured lever arm length on a shaft developing various amounts of recorded force on the wrench. Three preferred locations for the wrench are on (1) the kelly, (2) the rotary drive shaft, or (3) the stub extension of the rotary counter shaft. FIGURE 8 is a diagram of the calibration being made on the stub extension of the rotary counter shaft 801. Rotary counter shaft 801 is directly related to the shaft of prime mover 59. The wrench has a turnbuckle 806 attached thereto, a tension measuring device 808, and a winch line 810, successively. The tension cell 808 (strain gauge type) gives a signal output proportional to the tension on the wrench handle. The signal, together with the output signal of the torque transducer, is recorded continuously during a calibration. The calibration is then started by locking the rotary table and releasing the clutch on the rotary counter shaft. The winch line is tightened until the slack is removed. Additional tension is then placed on the wrench handle by means of the turnbuckle. The tension in the line is increased until the torque is developed well above the expected value of torque to be encountered during drilling operations. The tension is then gradually released by means of the turnbuckle, giving a complete series of ascending and descending measured values of torque. As illustrated in FIGURE 3, wherein a block 309 represents a means for generating a torque calibration function, the torque calibration signal is fed into the recorder, represented by block 39, in the same manner as the torque function signal. By generating the signals simultaneously during calibration and using a multipen recorder having a sufficient number of channels, the torque and torque calibration functions can be compared. Throughout the calibration the right angle projection of the lever arm in relation to the tension line is measured from the center of the shaft by means of an oversize square. The lever arm is measured quite frequently to compensate for any bending of the wrench handle during calibration.

A fifth function representative of the pressure of the drilling fluid is generated as described below. Referring again to FIGURE 1, the pressure on the drilling fluid being circulated is monitored on the discharge manifold 69 of the fluid pump 19. A standard BLH pressure cell which is available from Waltham, Massachusetts is used for this purpose. The means for generating a function output representing fluid pressure, designated by a block 311, is connected, as shown in the block diagram of FIGURE 3, through the control equipment 38 to the recorder 39. The electrical schematic of the means for generating the function representative of the pressure of the drilling fluid is shown in FIGURE 4 as that portion of the circuit also indicated by indicia 311. Therein the usual balanceable bridge circuitry and principle is employed as described above. Active strain gauges 459 are temperature compensated by dummy strain gauges 461 in the BLH pressure cell 463. The Wheatstone bridge is balanced by potentiometer 465 and powered a constant voltage source such as battery 403. Range of the pressure monitor is changed by rheostat 467. Change in pressure causes a change in the function generated and causes a deflection of galvanometer 469. As with the torque, we have often used filters, shown by dotted capacitor 471, to remove high frequency oscillations. Mechanical and hydraulic damping has also been used as the filter. Here, too, the high frequency components convey information which is empirically useful. The curve produced will vary widely, depending on the filtering used. One example is shown as curve 525, FIGURE 5.

A function representative of the flow or rate of circulation of the drilling fluid is generated by attaching a D.C. generator 70 (FIGURE 1) to the shaft of the fluid circulation pump 19. This attachment may be mechanical or simply a friction wheel, similar to that described above for the penetration. We prefer the latter. Since the pump 19 is a positive displacement pump, the r.p.m., or rate of rotation, is directionally proportional to the flow of drilling fluid being circulated. The D.C. voltage output is porportional to r.p.m. and hence is a function representative of the flow of drilling fluid. In FIGURE 3 the means for generating this latest discussed function is indicated as block 313. A signal generated by the block 313, representing the flow of fluid, is then fed to the control circuit 38, hence to the recorder 39. The electrical schematic of the means for generating the function representative of the rate of circulation of the drilling fluid is shown in FIGURE 4 as that portion of the circuit also indicated by indicia 313. It operates the same and has the same counterparts as the circuit portion 305 shown for generating a function representative of rate of rotation. That is, D.C. generator or tachometer 475 generates a function in the form of a voltage output as did tachometer 701. The function is carried as illustrated by circuit portion 313 in FIGURE 4 through potentiometer tap 479 and resistor 483 to drive galvanometer 485. Capacitors 477 and 481 are used to filter and improve function. A record similar to curve 529 in FIGURE 5, reading in units of volume per unit of time, e.g., gallons per minute or cubic feet per hour, is produced.

As a recording means for recording the functions representing, respectively, the penetration of the bit into the formation, the weight on the bit, the rate of rotation of the drill string, the torque imparted to the drill string, the pressure on the drilling fluid being circulated, and the flow of the drilling fluid being circulated, we have used two different recorders. The first to be used was a 10-channel general purpose Heiland Model 906–A Visicorder. While this gave us a galvanometer response ranging from 24 to 2000 c.p.s., we did not need such high frequency response characteristics. The recorder had the disadvantage that a high pressure mercury vapor lamp produced a light which was reflected from the galvanometers to record the various readings on light-sensitive paper. This had to be developed and did not provide a permanent record without subsequent photostating or fixing with a chemical solution. On subsequent models we have used a 6-channel pen recorder (commercially available from Westronics, Inc., Fort Worth, Texas). The recorder pen moves responsively to the various functions generated representing the drilling variables just as did the galvanometers in the foregoing descriptions. While advantageous in many ways, including the fact that it allows production of a very compact instrument, the 6-pen recorder is disadvantageous in that it limits the number of variables which can be recorded. Depths can be marked on the record to afford a recording with respect to depth as the independent variable.

An alternate and more elaborate embodiment which we have found useful in analyzing our drilling operations has been the use of an instrumented subassembly located in the drill string just below the floor of the drilling rig. This was discussed in detail before the International Instrumentation Symposium in Canada, June 5–8, 1961; and reported in its proceedings. In essence, the embodiment is described below. It will be readily apparent that details are given by way of illustration only and do not limit the use of the embodiment to the specific details given. Referring to FIGURE 9, the "sub" **901** has bonded thereon and aligned with its longitudinal axis two strain gauges **903** mounted diametrically opposite each other. Strain gauges **905** afford temperature compensation for these tension monitoring straing gauges. That is, strain gauges **905** are connected as the other arm in the Wheatstone bridge circuit, as illustrated by the hookup for weight on the bit **303** in FIGURE 4. Thus, temperature changes affect both resistances equally. Strain gauges **905** are not bonded to the "sub" as are strain gauges **903**, but are retained in place under close fitting shield **908** banded onto the exterior of the "sub." When bonded transversely, strain gauges **905** sensed pulsations in drilling fluid pressure and hence were unsatisfactory. The strain gauges **903** thus monitor tension or hook load and, hence as discussed above, can be used to generate a function representative of either, each, or both weight on the bit and vibrations, since they are extremely accurate and stable.

The "sub" also has four other strain gauges **910** and **912**, two each bonded thereon at 90° to each other and each at 45° to the longitudinal axis of the "sub." The entire transducer array on the exterior of the "sub" is protected by a sealed outer cover **913**. The strain gauges **910** and **912** both monitor the torque and afford temperature compensation using the same standard Wheatstone bridge circuitry used with gauges **903** and **905**. This can be seen in unfolded schematic form in FIGURE 10. There, the eight leads and the ground shield can be seen. These are conducted inside the "sub" and up the interior of the kelly with about 52 feet of cable **915** (FIGURE 9) to nine slip rings **918** located on a special "sub" **920** located between the kelly and the swivel. The electrical contacts on the slip ring are connected through suitable control equipment **38** (not shown) to the recorder **39** (not shown). In this manner, a function representative of the torque can be very accurately generated and temperature compensation afforded.

While one skilled in the art could construct a drilling information gathering system from the description given, listed below are some illustrative component values we have found to work very satisfactorily:

Potentiometer **401**—1,000 ohms.
Battery or constant voltage source **403**—30 volts.
Galvanometers **405**, **437**, and **485**—Minneapolis-Honeywell (M-H) type V450–55B.
Strain gauges **411**, **413**, **441**, **443**, **459**, **461**, **903**, **905**, **910**, and **912**—500 ohms nominal resistance.
Potentiometers **415**, **445**, and **465**—100,000 ohms.
Rheostats **417** and **447**—5,000 ohms.
Capacitor **421**—20 microfarads.
Galvanometers **419** and **449**—M-H type V40–1000.
Capacitors **432**, **434**, and **477**—10 microfarads.
Capacitor **481**—100 microfarads.
Resistor **436**—50,000 ohms.
Capacitor **451**—20 microfarads.
Rheostat **467**—2,000 ohms.
Capacitor **471**—20 microfarads.
Potentiometers **430** and **479**—10,000 ohms.
Resistor **483**—2,000 ohms.

All of the above-described embodiments provide data which are accurate enough for optimizing or comparing various drilling procedures. It will be apparent that more instrumentation can be recorded simultaneously. For example, as shown in FIGURE 3, by a block **306** designating a means for generating a function representative of vibrations of the drill string, we have on occasion recorded vibrations of the drill string. During offshore drilling operations, it would be useful to record the position of the drilling barge with respect to the borehole. Many other helpful variables can be recorded using our system. None are as universally vital as having simultaneously recorded, positively correlatable records, of at least the drilling rate, weight on bit, rate of rotation of the drill string, torque imparted to the drill string, pressure of the drilling fluid, and circulation rate of the drilling fluid. Preferably, these variables should be recorded on a unitary record. Having a good record, similar in quality to the section shown in FIGURE 5, of at least these six variables is necessary to proper control, engineering, and analysis of drilling operations. For clarity, both FIGURE 1 and FIGURE 5 illustrate a record wherein functions do not overlap. Where the record produced is small, e.g. six inches wide, overlapping of the scales of the recorded functions will be necessary. Provision is made for movement of the scales to prevent different functions being recorded on the same trace.

The system operates well under normal atmospheric conditions. Where high or low temperatures and/or high humidity is encountered, it becomes advisable to provide an enclosure for housing the control equipment and the recorder. It is vital that at least the recorder and its record be housed in an environment where temperature and humidity is controlled, if electronic difficulties, inadequate recorder response, and record distortion are to be prevented. It is advantageous to house any electronic components, relay panels, power supplies, etc. that space in enclosure will allow. To control both the temperature and humidity, conventional, commercially available heaters, air conditioners, and/or dehumidifiers are used with common thermostats and/or humidistats. In our work, we simply use a small, approximately 3' x 4' x 7', cubicle, having relatively air tight openings. A single, electrically powered, one-half ton air conditioner provides adequate refrigeration to keep both temperature and humidity within control. A small, electrically powered, circulating heater is adequate to keep the temperature high enough.

We have described and will use our invention to record the variables simultaneously. It is within the scope of our invention to use and we have experimented with programmed recorders which are commercially available to sample periodically the functions representing the drilling variables. While the record thus produced is not as good as the simultaneous recording, it can be very useful when employed in the manner of our invention.

We have described with particularity the drilling information gathering system which we have designed and built over several years. This system is designed for accuracy, simplicity, durability, and portability. It can be installed on any standard rotary drilling rig with approximately an hour of down time. It is amenable to recording of the data on magnetic tape or directly into digital computing equipment, as well as further automation of the drilling operation. We have used it in determining accurate experimental tests and stresses in the drill strings simultaneously with revamping and improving the recording system itself. The scope of our invention should be limited only by the appended claims.

We claim:

1. A drilling information gathering system for optimizing drilling by a drilling rig wherein a power rotating means delivers torque to rotate a drill string suspended from a traveling block moving in response to movement of a cable arranged over multiple sheaves mounted in a crown block, and turning a bit drilling a borehole into subsurface formations while circulating a drilling fluid to keep the bit and bottom of the borehole cleaned of cuttings, which comprises in combination:

(a) means for generating a first function representative of penetration of the bit into the subsurface

formation, which means comprises a wheel mounted in juxtaposition selected sheave in said crown block for controllable proportioning movement and trouble-free operation, and responsive to rotational movement thereof, a constant voltage D.C. powered, 360°, single-turn, continuously rotatable potentiometer connected to said wheel and moving in proportion to rotational movement thereof to generate said first function accurately representing small and large movements of said bit with respect to time,

(b) means for generating a second function representative of weight on the bit,

(c) means for generating a third function representative of the rate of rotation of the drill string,

(d) means for generating a fourth function representative of torque imparted to the drill string,

(e) means for generating a fifth function representative of pressure of the drilling fluid,

(f) means for generating a sixth function representative of the flow of drilling fluid, and

(g) recording means producing a unitary record, coupled to all of said function generating means and responsive thereto for simultaneously and correlatively recording on said unitary record with respect to an independent variable at least said six functions for meaningful technical analysis and control.

2. An apparatus for generating a function representative of penetration of the bit drilling a borehole into a subsurface formation where said bit is fixed to a drill string suspended from a traveling block moving in response to movement of a cable arranged over one or more sheaves mounted in a crown block, which comprises:

(a) a wheel mounted in juxtaposition a selected sheave in said crown block for controllable proportioning and trouble-free operation, and responsive to rotational movement thereof,

(b) a constant voltage D.C., 360°, single-turn, continuously rotatable potentiometer connected to said wheel and responsively movable in proportion to rotational movement thereof to generate the function accurately representating small and large movements of said bit, and

(c) a recorder connected to said potentiometer and recording with respect to time said function to produce a continuous record, the slope of which indicates whether going in or coming out of the borehole and the rate of penetration of the bit.

3. The apparatus of claim 2 wherein said potentiometer of step (b) is constructed of resistive plastic.

4. A drilling information gathering system for optimizing drilling by a drilling rig wherein a power rotating means delivers torque to rotate a drill string turning a bit drilling a borehole into subsurface formations while circulating a drilling fluid to keep the bit and bottom of the borehole cleaned of cuttings, which comprises in combination:

(a) means for generating a first function representative of penetration of the bit into the subsurface formation,

(b) means for generating a second function representative of weight on the bit,

(c) means for generating a third function representative of the rate of rotation of the drill string,

(d) means for generating a fourth function representative of torque imparted to the drill string,

(e) means for generating a fifth function representative of pressure of the drilling fluid,

(f) means for generating a sixth function representative of the flow of the drilling fluid,

(g) means incorporating a strain gauge and a power source, said strain gauge being connected in an electrical circuit with said power source and physically attached to a member integrally movable with, and bearing part of the weight of, said drill string whereby said strain gauge modifies the electrical signal from said power source in response to changes of tension in said member for generating a seventh function representative of the vibrations being transmitted up the drill string, and

(h) recording means producing a unitary record, coupled to all of said function generating means and responsive thereto for simultaneously and correlatively recording with respect to an independent variable, at least said seven functions for meaningful technical analysis and control.

5. A method of optimizing a drilling operation wherein a power rotating means turns a drill string having attached thereto a bit drilling a borehole into subsurface formations while circulating a drilling fluid to keep the bit and bottom of the borehole cleaned of cuttings, which method comprises the steps of:

(a) determining at least flow of the drilling fluid, rate of rotation of the drill string, weight on the bit, pressure of the drilling fluid, torque imparted to the drill string, and rate of penetration of the bit,

(b) increasing said flow of the drilling fluid while holding said rate of rotation and said weight on the bit substantially constant, and upon continuance of said pressure of the drilling fluid and said torque imparted to the drill string at their coordinated norms, measuring a first ratio of the increase of said rate of said penetration of the bit to the increase of said flow of the drilling fluid,

(c) increasing said rate of rotation of the drill string while holding said flow of the drilling fluid and said weight on the bit substantially constant, and upon continuance of said pressure of the drilling fluid and said torque imparted to the drill string at their coordinated norms, measuring a second ratio of the increase of said rate of penetration of the bit to the increase in said rate of rotation of the drill string,

(d) increasing said weight on the bit while holding said flow of the drilling fluid and said rate of rotation of the drill string substantially constant, and upon continuance of said pressure of the drilling fluid and said torque imparted to the drill string at their coordinated norms, measuring a third ratio of the increase in rate of penetration of the bit to the increase in weight on the bit,

(e) repeating step (b) until said first ratio is within an optimum range wherein said first ratio is less than said first ratio of the preceding step (b) but greater than seventy percent of said first ratio of the preceding step (b),

repeating step (c) until said second ratio is within an optimum range wherein said second ratio is less than said second ratio of the preceding step (c) but greater than seventy percent of said second ratio of the preceding step (c),

repeating step (d) until said third ratio is within an optimum range wherein said third ratio is less than said third ratio of the preceding step (d) but greater than seventy percent of said third ratio of the preceding step (d), and

(f) conducting drilling operations in accordance with said drilling variables so optimized.

6. The method of claim 5 wherein said drilling variables so optimized are recorded with respect to the formation, locale, and depth on permanent, retrievable records.

7. The method of claim 5 wherein said increasing in steps (b), (c), and (d) is performed in equal increments whereby said accompanying and respective increases in said rate of penetration of the bit are representative of said first ratio, said second ratio, and said third ratio in said steps (b), (c), and (d), said first ratio, said second ratio, and said third ratio are easily measured, and said optimizing readily effected.

8. The method of claim 5 wherein said increasing in steps (b), (c), and (d) is performed sequentially until, respectively, said first ratio, said second ratio, and said third ratio are optimized.

9. The method of claim 5 wherein said increasing in steps (b), (c), and (d) is performed separately until each respective variable of said flow of the drilling fluid, said rate of rotation of the drill string, and said weight on the bit is optimized as described in step (e).

10. The method of claim 5 wherein said flow of the drilling fluid, said rate of rotation of the drill string, said weight on the bit, said pressure of the drilling fluid, said torque imparted to the drill string, and said rate of penetration of the bit are recorded on a unitary record.

11. The method of claim 5 wherein vibrations transmitted up the drill string are also determined in step (a) wherein said rate of rotation of the drill string in step (c) also is increased to produce a trace of vibrations transmitted up the drill string showing cyclic high-amplitude signals when drilling in the shallow portions of the borehole or to produce a trace of vibrations transmitted up the drill string showing cyclic low-amplitude signals when drilling in the deep portions of the borehole.

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