Feb. 23, 1954

A. LUBINSKI

2,669,871

WEAR OF BIT INDICATOR

Filed March 29, 1949

3 Sheets-Sheet 1

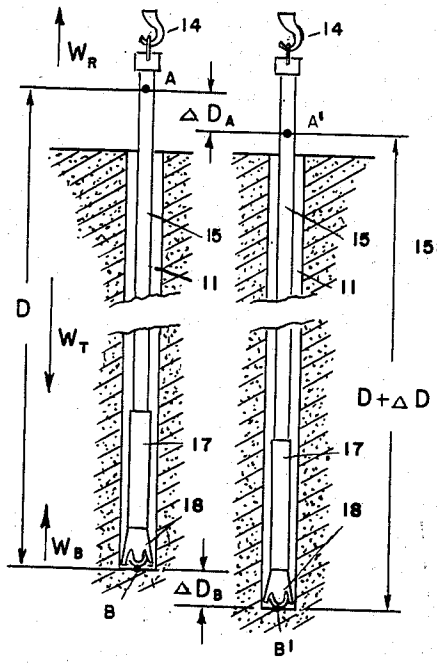


FIG 1A FIG 1B

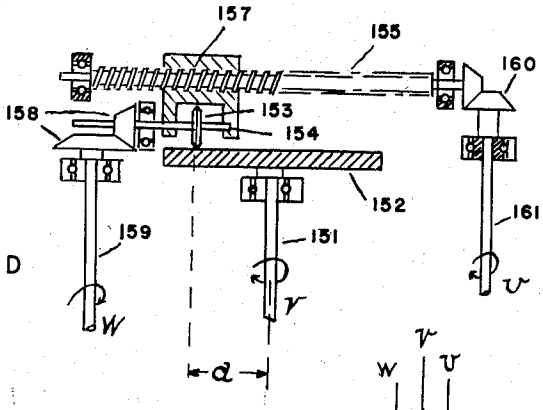


FIG 4

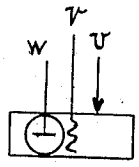


FIG 4A

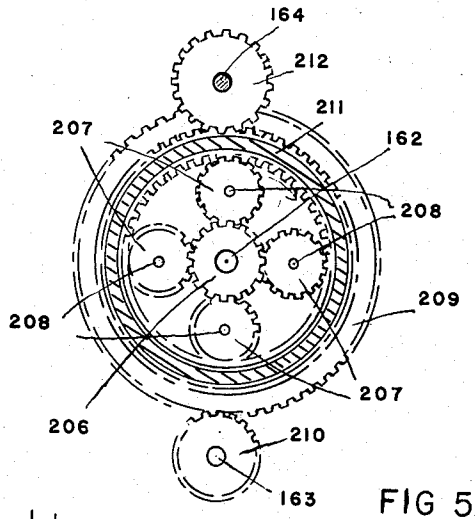


FIG 5B

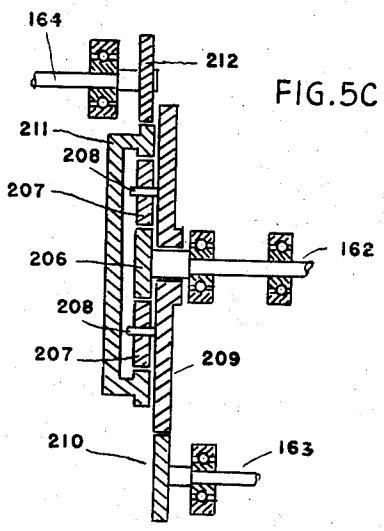


FIG.5C

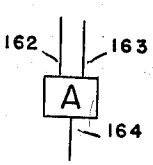


FIG 5A

INVENTOR.

BY Arthur Lubinski

Feb. 23, 1954 A. LUBINSKI 2,669,871

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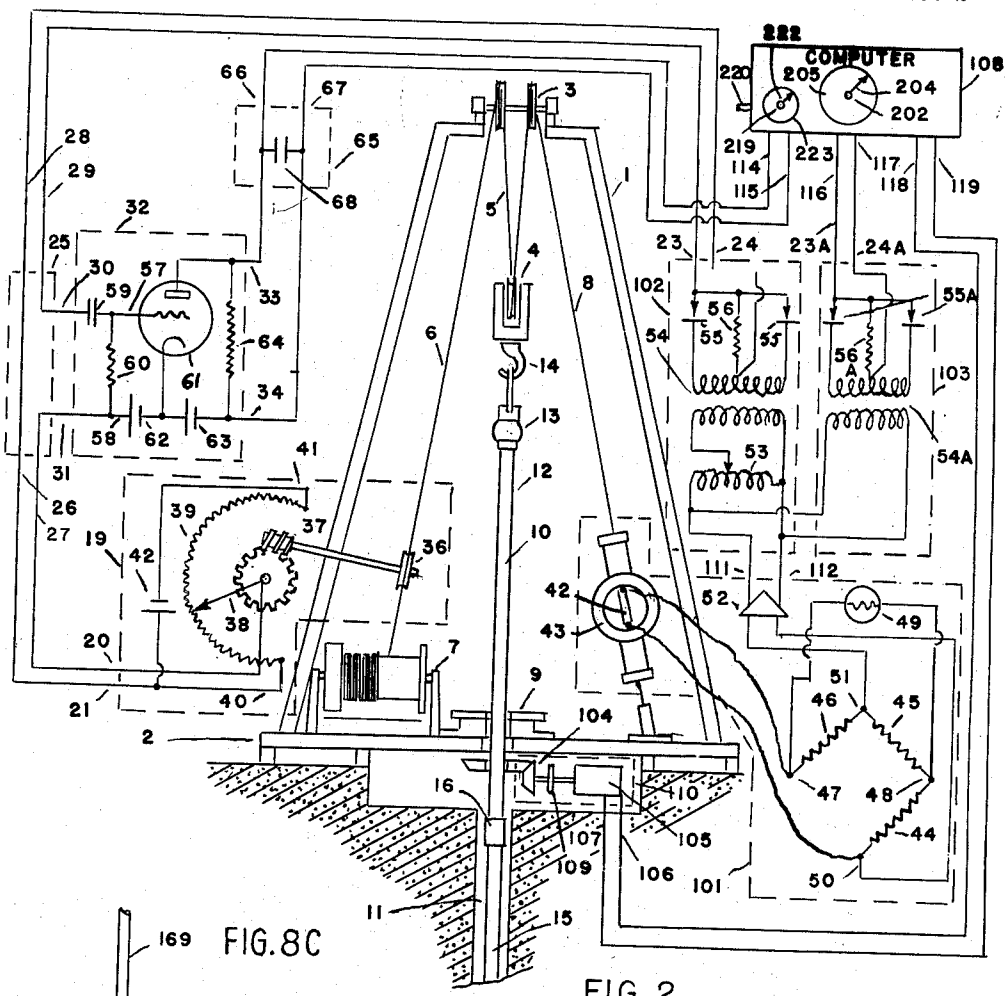


FIG 2

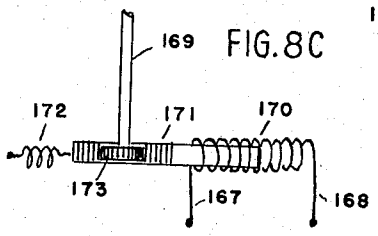


FIG. 8C

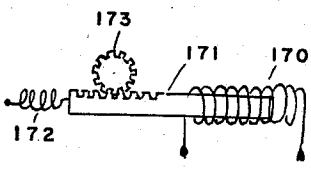


FIG. 8B

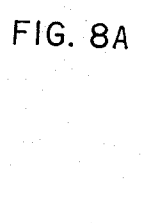
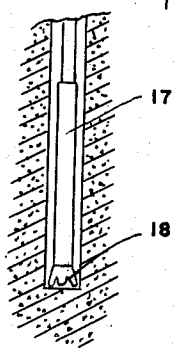


FIG. 8A



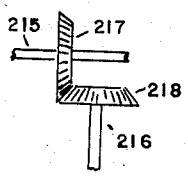


FIG. 9

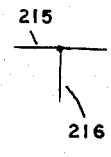


FIG 9A

INVENTOR.

BY Arthur Lubinski

Feb. 23, 1954 A. LUBINSKI 2,669,871

WEAR OF BIT INDICATOR

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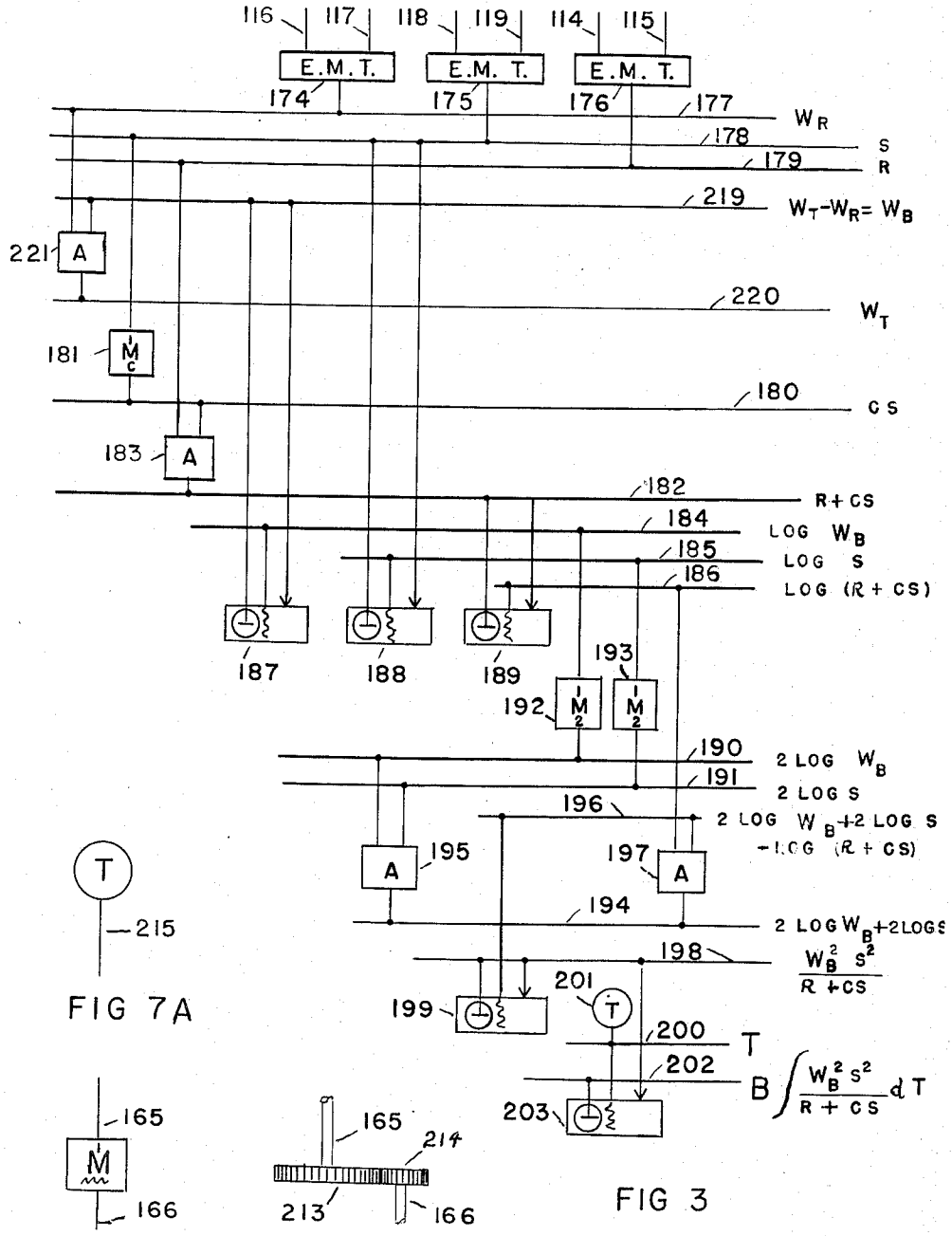


FIG 3

FIG 7A

FIG 6A

FIG 6

INVENTOR.

BY Arthur Lubinski

Patented Feb. 23, 1954

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UNITED STATES PATENT OFFICE

2,669,871

WEAR OF BIT INDICATOR

Arthur Lubinski, Tulsa, Okla.

Application March 29, 1949, Serial No. 84,215

12 Claims. (Cl. 73—151)

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This invention relates to an improvement in instrumentation to be used in drilling of oil wells and has particular reference to an arrangement for producing an indication of the wear of bit used in drilling.

When drilling in very hard formation, a bit may be worn out in less than one hour. In soft formation it may be in good condition after many days of service. When the drilling slows down, the driller does not know whether the bit is worn out, or a hard formation is encountered. The importance of ascertaining the degree of wear of the bit has been recognized in the past, but no satisfactory solution of the problem has been found because the most essential element causing the wear, i. e. the hardness of the formation drilled is unknown while drilling.

It is the purpose of this invention to obviate the inconveniences of the prior art and to provide the driller with an instrument indicating on the surface the degree of wear of the bit.

It is another purpose of this invention to provide an instrument that may be incorporated in a great variety of measuring devices used in drilling operations.

Other and more specific objects of this invention will be readily apparent from the following detailed description when read in conjunction with the accompanying drawings which illustrate a form of the apparatus of this invention.

In the drawings:

Fig. 1A and Fig. 1B show schematically certain factors affecting the operation of the proposed device at two succeeding times.

Fig. 2 shows the details of the wear of bit indicating instrument in conjunction with conventional drilling equipment.

Fig. 3 shows the general schematic arrangement of the computer.

Fig. 4 shows the details of an integrating element.

Fig. 4A shows the symbol used for an integrating element of the type shown on Fig. 4.

Fig. 5A shows the symbol used for an adding element of the type shown on Fig. 5B and Fig. 5C.

Fig. 5B and Fig. 5C show two mutually perpendicular cross sections of the adding element.

Fig. 6 shows the details of a multiplying element.

Fig. 6A shows the symbol used for a multiplying element of the type shown on Fig. 6.

Fig. 7A shows the symbol used for a timing motor.

Fig. 8A shows the symbol used for an electromagnetic transducer of the type shown on Fig. 8B and Fig. 8C.

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Fig. 8B and Fig. 8C show two mutually perpendicular cross sections of the electromagnetic transducer.

Fig. 9 shows the details of bevel gears for transmission of motion between two perpendicular shafts.

Fig. 9A shows the symbol used for a perpendicular transmission of motion of the type shown on Fig. 9.

This invention is a result of a discovery that the rate of wear of the bit designated by a symbol B is a function which may be expressed as follows:

$$B=\int_0^T \varphi(W_B, r, s)dT \qquad (1)$$

where

W_B is the weight on bit, i. e. the force applied by the bit to the bottom of the hole. W_B is measured in thousands of pounds.

r is the rate of drilling in feet per hour.

s is the number of revolutions per hour of the rotary table.

T is the drilling time in hours. T is equal to zero when the drilling starts with a new bit.

The function B defined by the Expression 1 increases in value with the wear of the bit and reaches a preassigned limiting value when the bit becomes dull.

I have chosen as an example a particular form of the Expression 1, as follows:

$$B=\int_0^T \frac{W_B^2 s^2}{r+cs}dT \qquad (2)$$

where c is an appropriate constant depending on the kind and on the size of the bit.

As an illustration of the values of constants in the Formula 2 we may choose a rock bit W7R, size 9'' manufactured by Hughes Tool Company. We obtain then

$$c=4\times10^{-5}\ \frac{\text{feet}}{\text{revolution}}$$

for a dull bit:

$$B=400\times10^{8}\ \frac{\text{Rev}^2(\text{Lb.}\times1000)^2}{\text{Foot}}$$

We shall examine now more in detail the rate of progress of the drill bit designated by symbol r in the Expressions 1 and 2 and we shall consider in that connection Fig. 1*a*, 1*b*, showing, respectively, the positions of the drilling string at an instant T_0 and at a suitable later instant $T_0+\Delta T$. In both figures the numeral 11 designates the bore hole in process of being drilled. The drill string comprises a drill pipe section 15

extending from the top of the bore downwards. A heavy and thick drill pipe **17** is fastened to the lower portion of the drill pipe and is provided at its lower end with the drill bit **18**.

The drill string is subjected during the drilling process to variable tension and therefore its length varies. Of particular interest to the driller are two portions of the drill stem that are represented by points A and B. The point A is located on the top of the drill stem directly above the earth surface. The motion of the point A is directly observable by the driller and can be indicated by means of a suitable arrangement. The point B is located at the lower extremity of the drill string at the bottom of the bore hole. The distance between A and B designated by D represents the length of the drill stem and because of the elasticity of the drill pipe the length D usually undergoes variations caused by variation of corresponding forces.

To use the Formulae 1 or 2 we have to produce an indication of the rate of progress of the bit, and therefore we are particularly interested in determining the downward motion of the lower extremity of the drill represented by the point B. This point is, however, entirely inaccessible to direct observation, and the problem consists therefore in deriving from the motion of point A (directly observable) and from certain factors controlling the length of the drill string, the desired indication of the downward progress of the point B.

Consider now an instant $T_0+\Delta T$ represented in Fig. 1*b*. The point A has moved downward to a position A^1 distant from A by the amount ΔD_A, the point B has moved downward to the position B^1 distant from B by the amount ΔD_B and the new length of the drill string represented by the distance A^1B^1 has now increased to a value $D+\Delta D$. From the inspection of Fig. 1*a* and 1*b* it is seen that the following relation holds true:

$$AB+\Delta D_B=\Delta D_A+A'B' \tag{3}$$

or

$$D+\Delta D_B=\Delta D_A+D+\Delta D \tag{4}$$

whence

$$\Delta D_B=\Delta D_A+\Delta D \tag{5}$$

or

$$\frac{\Delta D_B}{\Delta T}=\frac{\Delta D_A}{\Delta T}+\frac{\Delta D}{\Delta T} \tag{6}$$

It is desired to produce an indication of the value $\Delta D_B/\Delta T$ representing the rate of progress of the bit and it is seen that this value can be determined by separately producing signals representing values $\Delta D_A/\Delta T$ and $\Delta D/\Delta T$ and subsequently adding these signals.

The value $\Delta D_A/\Delta T$ represents the downward motion of the upper extremity of the drill stem and is represented by means of a suitable arrangement that shall be explained hereafter.

The signal $\Delta D/\Delta T$ representing the rate of change of the length of the drill pipe can be determined by means of the following considerations:

As stated above, the drilling string consists of a relatively thin pipe section **15** which is provided at the lower extremity by a thick pipe **17** designated as drill collars which in turn are fastened at their lower ends to the drill bit **18**.

It is apparent to those skilled in the art that the drill string is subjected to internal tensions (or compressions) that are not uniform throughout its length, but decrease with the depth. Thus, for instance, the upper portions of the drill string in the neighborhood of the point A are subjected to a tension substantially equal to the weight suspended from the hook **14**. Let W_R designate this weight. As we progress downward, the tension decreases and at a certain critical depth it becomes equal to zero. This critical depth is located below the drill pipe section somewhere within the drill collars section. The section located immediately below this depth is subjected to a small compression and this compression increases with the depth as we approach the point B at the bottom of the hole. At this depth the compression is equal to the weight on the bit. Let W_B designate this weight.

It is therefore apparent the longest portion of the drill string consists of the drill pipe **15** and is subjected only to tension which causes its elastic elongation. The relatively short section of the drill collars is subjected to compression, but the corresponding elastic deformation is negligible because the thick drill collars are practically non-elastic.

We can therefore consider the overall picture by assuming that the total drill string is subjected to an elastic elongation, and consequently the corresponding variation ΔD in the length of the drill string can be represented as

$$\Delta D=K\Delta W_R \text{ where K is a constant} \tag{7}$$

$$\frac{\Delta D}{\Delta T}=K\frac{\Delta W_R}{\Delta T} \tag{8}$$

Consequently, the signal representing the rate of change in the length of the drill stem can be replaced by the signal representing the rate in change in the force W_R multiplied by an appropriate coefficient.

Substituting 3 in 6 we obtain for the desired signal representing the rate of progress in the bit an expression as follows (in the limiting case for $\Delta T\to 0$):

$$\frac{dD_B}{dT}=\frac{dD_A}{dT}+K\frac{dW_R}{dT} \tag{9}$$

It is apparent from the Expression 9 that in order to produce the desired indication

$$\frac{dD_B}{dT}$$

representing the progress of the drill bit two separate indications are required; namely, the indication

$$\frac{dD_A}{dT}$$

representing the progress of the upper extremity of the drill string and the indication

$$K\frac{dW_R}{dT}$$

representing the rate of change of the weight. We may modify somewhat the problem and express the Formula 9 as follows:

$$\frac{dD_B}{dT}=\frac{d}{dT}(D_A+KW_R) \tag{10}$$

Consequently, as expressed by the Formula 10 the desired result may be obtained by separately producing a signal representing the value D_A corresponding to the downward displacement of the upper extremity of the drill string, and separately producing another signal, W_R representing the weight suspended on the hook **14**. These two signals are subsequently added to form a signal (D_A+KW_R) and subsequently another signal is produced that represents the time derivative of the sum (D_A+KW_R). This latter gives the desired indication representing the rate of drilling, i. e. the value r in the Formulae 1 and 2.

Consider now Fig. 1A in which

W_T designates the total weight of the drilling string.

W_R designates the weight suspended from the hook 14, i. e. the weight read on the weight indicator, and

W_B designates the weight on bit, or rather the upward reaction of the bottom of the hole against the drilling string.

Because of the vertical equilibrium of the drilling string, following relation holds true:

$$W_B = W_T - W_R \tag{11}$$

W_T may be easily measured by pulling the whole drilling string a few feet up, because it is obvious that W_T becomes then equal to the weight suspended from the hook 14. Therefore the Formula 2 may be written

$$B = \int_0^T \frac{(W_T - W_R)^2 s^2}{r + cs} dT \tag{12}$$

Consider now Fig. 2 representing a conventional rotary drilling rig. The principal portion of the arrangement shown consists of a derrick 1 mounted on a floor 2, crown block pulleys 3, from which a conventional traveling block 4 is suspended by means of the usual wire cables 5 terminating in the hoisting or drilling line 6. The drilling line is fed from the reel 7 by releasing a conventional brake, not shown. The movement of the hoisting or drilling line 6 about the crown pulleys 3 controls the raising and lowering of traveling block 4. The hoist line 6 after having passed about the crown block pulleys 3 and the traveling block pulley 4 terminates by the so-called dead line 8 which is anchored to the derrick. Mounted on the derrick floor is a conventional rotary table 9 through which the usual drilling string indicated at 10 extends into the well bore 11. Drilling string 10 consists of a rotary drive member or kelly 12 attached by a swivel 13 to a hook 14 suspended from traveling block 4, hollow drill pipe 15 connected by a coupling 16 to the kelly, a hollow thick drill collar section 17 and a drill bit 18 attached to the lower end of the drill collars. An engine drives the rotary table 9 through a chain, the sprocket 109 and the bevel gears 104. The engine and chain are not shown on the figure.

The wear of bit indicating instrument comprises the following essential elements:

(1) Means comprised within dotted line 19 for producing a signal D_A. An electric voltage representing the value D_A is thus produced across the output terminals 20 and 21.

(2) Means comprised within the dotted line 101 for producing a signal proportional to W_R. An electric A. C. voltage proportional to W_R is thus produced across the output terminals 111 and 112.

(3) Means comprised within the dotted rectangle 102 for producing a signal KW_R. An electric D. C. voltage is thus produced across the output terminals 23 and 24.

(4) Means for adding the signals D_A and KW_R comprised within the dotted rectangle 25. This means is provided with two pairs of input terminals designated by numerals 26, 27 and 28, 29 and one pair of output terminals 30, 31. The input terminals are connected in a manner so as to produce across the output terminals 30 and 31 a voltage equal to the sum of the two input voltages. Since the input voltages applied across the terminals 26, 27 and 28, 29 are respectively D_A and KW_R, then the resulting voltage across the output terminals 30, 31 represent D_A+KW_R.

(5) Means comprised within the dotted rectangle 32 for producing the time derivative of the signal D_A+KW_R. The means is provided with one pair of input terminals 30, 31 across which a voltage representing the signal D_A+KW_R is applied and one pair of output terminals 33 and 34 across which a voltage representing the signal

$$\frac{d}{dT}(D_A + KW_R)$$

is produced.

(6) Means comprised within the dotted rectangle 65 for damping the fluctuations due to vibrations and other reasons which frequencies are of the same order of magnitude. The means is provided with one pair of input terminals 33, 34 and one pair of output terminals 66, 67. The voltage across the output terminals 66 and 67 represents the rate of progress r with which the bit penetrates the formation.

(7) Means comprised within the dotted rectangle 103 for producing a D. C. signal W_R. An electric D. C. voltage representing the value of W_R is thus produced across the output terminals 23A and 24A.

(8) Means comprised within the dotted rectangle 110 for producing a signal s, i. e. a signal of the rotary angular velocity. An electric voltage representing the value of s is thus produced across the output terminals 106 and 107.

(9) A computer 108 for computing and indicating the values of the function B according to the Formula 12. The computer is provided with three pairs of input electric terminals 114—115, 116—117, and 118—119. The three input voltages represent respectively:

Across 114—115: r, or rate of drilling.
Across 116—117: W_R, or weight.
Across 118—119: s, or rotary angular velocity.

The computer 108 is also provided with a shaft 219 which drives the hand 222 in front of the dial 223 and which indicates the weight on bit W_B. Another shaft designated by the numeral 220 is set on an angular position corresponding to the total weight of the drilling string W_T. The setting has to be made immediately before starting drilling with a new section of drilling pipe 15 added to the drilling string. As indicated above, the total weight W_T of the drilling string, and consequently the setting of the shaft 220, can be determined when the bit is off bottom, and consequently the total weight of the drilling string is suspended on the hook 14. Under such condition, $W_B=0$ and the value W_T is indicated on the dial 223. The computer 108 is also provided with an output shaft 202, the angular position of which is proportional to B. The hand 204 in front of the dial 205 indicates the values of B.

Consider now more in detail the various means comprised into the wear of bit indicating arrangement in accordance with my invention.

(1) The means for producing the signal D_A (within the dotted line 19) comprises a pulley 36 driven by the hoist line 6 which in turn drives a worm gearing reduction 37 which moves the moving arm 38 of a potentiometer. The potentiometer comprises a semi-circular fixed resistor 39 having its terminals 40 and 41 supplied by a suitable battery 42. The arm 38 is provided at its extremity with a contact member adapted to slide upon the resistor in accordance with the motion of the gear. The output terminals

21 and 20 are respectively connected to the terminal 40 of the resistor and the moving arm 38. It is apparent that the output voltage across the terminals 21 and 20 represents in fact the potential drop in a portion of the resistor between the terminal 40 and the sliding contact of the moving arm 38 and, furthermore, this voltage is proportional to the total displacement of the hoist line which in turn is proportional to D_A.

(2) The means for producing a signal proportional to W_R and comprised within the dotted line 101 has as its essential element a strain responsive element 42. This element consists of a resistor having its two ends fastened by means of appropriately insulated terminals to a frame structure 43 which is in turn clamped to the dead line 8. The dead line is subjected to a tension which is proportional to W_R. This tension is transmitted to the frame structure 43 and to the strain responsive element 42 and causes a corresponding elongation of this element which in turn causes a corresponding change in the electric resistance of the element. Consequently, the resistance of the element 42 represents the tension W_R. The strain responsive element 42 is made to be one of the arms of a Wheatstone bridge, the remaining three arms of which consist of resistors 44, 45, and 46. The two terminals 47 and 48 of the bridge are supplied with an A.-C. voltage source 49. Consequently, the output voltage across the two bridge terminals 50 and 51 represents W_R. The same signal amplified in the amplifier 52 appears across the output terminals 111 and 112.

(3) The means for producing a signal representing KW_R (within the dotted rectangle 102) comprises a manually set autotransformer 53, a transformer 54, a two-wave rectifier 55, and a resistor 56. The autotransformer 53 may be of any commercial type such as the "Varitran" manufactured by General Electric. It produces a means of changing at will the ratio between the tension W_R and the output voltage across the terminals 23 and 24, said output voltage representing the value KW_R. Thus a suitable value may be given to the coefficient K (see Formula 10) in accordance with the elasticity of the pipe. It is well known that the elasticity of the drill pipe depends upon the type of the pipe and its length. Consequently the values of K have to be changed from time to time as the drilling progresses.

(4) The means for producing the time derivative of the signal D_A+KW_R (within the dotted rectangle 32) is adapted to perform the process of derivation electrically in such a manner that when it receives between its input terminals 30 and 31 a certain voltage it delivers across the leads 57 and 58 a voltage varying substantially as the derivative with respect to time of the input voltage. The derivator consists of a capacitor 59 inserted between the terminal 30 and the lead 57, and of the resistor 60 inserted between the terminal 31 and the lead 57.

The operation of the derivator can be explained mathematically as follows: Let $V_1(T)$ be the function representing the voltage applied across the input terminals 30 and 31 of the derivator, $V_2(T)$ the function representing the voltage across the terminal 58 and the lead 57, C the capacitance of the capacitor 59, P the resistance of the resistor 60 and $i(T)$ the current flowing through the capacitor 59. Assume also that the leads 57 and 58 of the derivator have been disconnected from the tube 61 and the battery 62. Consequently, the same current $i(T)$ flows through the capacitance 59 and through the resistance 60 and the following relation holds true:

$$V_1(T)=\frac{1}{C}\int_0^T i(T)dT+Pi(T) \qquad (13)$$

Differentiating the Equation 13, we obtain

$$\frac{dV_1(T)}{dT}=\frac{1}{C}i(T)+P\frac{di(T)}{dT} \qquad (14)$$

By selecting the proper values of the resistance P, for example making P negligibly small, the term

$$P\frac{di(T)}{dT}$$

can be made negligible as compared to

$$\frac{i(T)}{C}$$

and the following relation may hold with an approximation satisfactory for practical purposes:

$$\frac{dV_1(T)}{dT}=\frac{1}{C}i(T) \qquad (15)$$

Multiplying both sides of the Equation 15 by CP we obtain

$$CP\frac{dV_1(T)}{dT}=Pi(T)=V_2(T) \qquad (16)$$

Consequently the expression $Pi(T)$ which represents the voltage drop across the resistor 60 across the leads 57 and 58 is substantially proportional to

$$\frac{dV_1(T)}{dT}$$

which represents the time derivative of the input voltage across the terminals 30 and 31.

The voltage across the leads 57 and 58 is applied to the grid of a 3 electrode tube 61, the cathode of which is connected to the terminal 58 by means of a biasing battery 62. A suitable B battery 63 and a resistor 64 are connected in the plate circuit. The two terminals of the resistor 64 are connected respectively to the terminals 33 and 34. It is well known that for a suitable choice of the type of the tube 61 and batteries 62 and 63, the plate current is proportional to the grid voltage. As the plate current flows through the resistor 64 it is also proportional to the drop of voltage across this resistor, that is to say to the voltage across the terminals 33 and 34.

Consequently the voltage across the output terminals 33 and 34 represents the voltage across the leads 57 and 58 which is suitably amplified. As the voltage across the leads 57 and 58 is substantially proportional to the time derivative of the input voltage across the terminals 30 and 31, then the output voltage across the terminals 33 and 34 represents r, i. e. the rate of progress of the drilling bit into the formation.

(5) The means for damping the fluctuations of the voltage across the terminals 33 and 34 (within the dotted rectangle 65) without interfering with a sufficiently fast response of the instrument. The means comprises any kind of low-pass filter or simply a capacitor 68 shown on the Fig. 2.

(6) The means for producing a signal representing W_R comprised within the dotted rectangle 103 comprises the same parts as the means (3) comprised within the dotted rectangle 102 except the autotransformer 53, said autotrans-

former being excluded from means 103. Other elements in means 103, such as the transformer 54A, the rectifier 55A and the resistor 56A are identical to the corresponding elements 54, 55 and 56 of the means (3). It is apparent that the output voltage of the rectifier 55*a*, i. e. the voltage across the terminals 23A and 24A is representative of the weight W_R.

(7) The means for producing a signal representing *s* comprised within the dotted rectangle 110 comprises as its essential element the tachometer generator 105 driven by the rotary table 9 through the bevel gears 104. It is obvious that the output voltage of the generator across the output terminals 106 and 107 represents the rotary angular velocity *s*.

(8) The general arrangement of the computer is drawn diagrammatically on Fig. 3. Various elements of this arrangement are illustrated on Figures 4, 5B, 5C, 6, 8B, 8C, and 9 and various symbols on Figures 4A, 5A, 6A, 7A, 8A, and 9A.

Figs. 4 and 4A show an integrating element which comprises two input shafts 151, 161 and one output shaft 159. The angular displacement of the output shaft 159 depends upon the angular displacements of the input shafts 151, 161 in accordance with a definite functional relationship which may be expressed as follows:

$$W=\int_{V_1}^{V_2} U dV \qquad (17)$$

in which

U designates the angular displacement of the shaft 161

V designates the angular displacement of the shaft 151, and

W designates the angular displacement of the shaft 159

The input motion V is imparted to the shaft 151 which rotates a flat disc 152 about a vertical axis. A sharp-edged wheel 153 rests on the disc and is driven by friction so as to produce the output rotation W of the shaft 159 when the disc is turned. The shaft 159 is driven by the wheel 153 through the spline shaft 154 and bevel gears 158. One of the bevel gears 158 is slidingly mounted on the spline shaft 154. The motion U displaces the spline shaft 154 along the direction of the axis of the said shaft. During the displacement the bevel gears 158 are continuously engaged one to another. The input motion U is applied to the shaft 161 which drives the threaded shaft 155 through the bevel gears 160. The shaft 155 moves the nut 157 carrying the output wheel 153. Let *a* designate the distance between the wheel 153 and the axis of the shaft 151. It is apparent that the ratio between the angular displacements of the shafts 154 and 151 is equal to the ratio of *a* and the radius of the wheel 153. On the other hand, the value *a* is evidently proportional to U. Consequently we have the following relation:

$$\frac{dW}{dV}=bU \qquad (18)$$

where *b* is a constant of the integrator. The Equation 18 gives

$$W=b\int_{V_1}^{V_2} U dV \qquad (19)$$

By a suitable choice of units, dimensions, and of the ratio of gears 158, *b* can be made equal to one and the integrator will operate according to the Formula 17. Consequently if the shafts 161 and 151 are driven so as to assume successive angular positions in accordance with the successive values of functions U and V, then the angular positions of the shaft 159 are equal to the values of the function W as defined with the Formula 17.

The integrator is also used in the computer to generate natural logarithms. If the shafts 159 and 161 are connected so that their displacements are identical, then the angular positions of the shaft 151 are the natural logarithms of the angular positions of the shafts 159 and 161. Then, when used to generate natural logarithms, the input shafts are 159 and 161 and the output shaft is the shaft 151.

The mathematical explanation is as follows: If $y=\log_e x$, then

$$\frac{dy}{dx}=\frac{1}{x}$$

and $dx=xdy$

$$x=\int x dy \qquad (20)$$

Comparing this equation with the Equation 17 it is seen that if the functions W and U are identical, i. e. $W=U$, then V corresponds to *y*, i. e. $V=\log_e U$ or $V=\log_e W$.

Consider now Figures 5A, 5B, and 5C illustrating a means for adding two values and designated as "adder." An adder is an instrument provided with two input shafts 162 and 163 and one output shaft 164. The motion of the shaft 164 is equal to the sum of motions of the shafts 162 and 163, i. e. that the shafts are interconnected in such manner that at any moment the angular displacement of the shaft 164 is equal to the sum of the angular displacements of the shafts 162 and 163. An adder is essentially a differential of any type. A planetary differential was drawn on Figures 5B and 5C. The input shaft 162 drives the gear 206 which drives the four planetary gears 207 placed on the four small shafts 208. The small shafts 208 are fastened on the gear 209 driven by the input shaft 163 through the gear 210. The four planetary gears 207 drive the gear 211 which drives the output shaft 164 through the gear 212. The input shaft 162 and the gear 206 impart to the planetary gears 207 a motion which is a revolution about their axis. The input shaft 163 and the gears 210 and 209 impart to the planetary gears 207 a motion which is a revolution of their axes about the axis of the shaft 162. Consequently, the four planetary gears 207 impart to the gears 211 and 212 and to the output shaft 164 a motion which is a function of the two input motions. It may be clearly seen by those skilled in the art that by a proper choice of gears the motion of the output shaft 164 may be equal to the sum of the motions of the two input shafts 162 and 163.

In the computer described here, the adder is sometimes used as a subtractor. In such case the input shafts are 164 and 162 and the output shaft is the shaft 163. The motion of the shaft 163 is the difference of the motions of the shafts 164 and 162.

Consider now Figures 6 and 6A illustrating a means for multiplying a variable value by a constant factor *m* and designated as "multiplier." A multiplier comprises two gears 213 and 214 and two shafts 165 and 166. The input shaft 165 drives the gear 213 which drives the gear 214 which in turn drives the output shaft 166.

The ratio of number of teeth of the gears 213 and 214 is equal to the constant factor *m* of the multiplier.

Consider now Fig. 7A which shows diagrammatically a timing motor driving an output shaft **215** with a constant angular velocity. Any type of a commercially available synchronous motor, or a clock driven motor are suitable for the purpose.

Figures 8A, 8B, and 8C illustrate an electromagnetic transducer which is essentially an instrument transforming a D. C. voltage into angular positions of a shaft. The transducer is provided with a pair of electric input terminals **167** and **168** and an output shaft **169**. The angular positions of the output shaft **169** are proportional to the input voltage across the terminals **167** and **168**. The transducer comprises essentially a solenoid attracting a bar magnet **171** which movement is opposed by a spring **172**. The magnet is provided with a rack driving the pinion **173** so the rectilinear motion of the rack is transformed into a rotation of the pinion **173** which rotates the output shaft **169**.

Figures 9 and 9A illustrate a very simple means used in the computer for driving a shaft **216** by another shaft **215** perpendicular to the first. The means comprises two bevel gears **217** and **218**.

Consider now the general computer arrangement shown in Fig. 3. The arrangement is provided with three pairs of input terminals **116**—**117**, **118**—**119**, and **114**—**115** shown also in Fig. 2. These input terminals bring to the computer three signals that represent respectively:

(*a*) the value W_R or weight suspended from the hook
(*b*) the value *s* or rotary table angular velocity
(*c*) the value *r* or rate of drilling

The three electromagnetic transducers **174**, **175**, and **176** transform the input electric signals into mechanical motions of the shafts **177**, **178**, and **179**.

The input shaft **220** must be set manually on an angular position corresponding to the total weight of the drilling string W_T. The shafts **220** and **177** drive the shaft **219** through the adder **221** connected as a subtractor. As stated above the angular positions of the shaft **177** correspond to W_R. Consequently the angular position of the shaft **219** is always equal to $W_T - W_R$ which is equal to W_B according to the Formula 11.

The shaft **178** drives the shaft **180** through the multiplier **181** of ratio C. The motion of the shaft **180** is *cs*. *c* is a constant defined in connection with the Formula 2.

The shafts **179** and **180** drive the shaft **182** through an adder **183**. Thus the motion of the shaft **182** is $r+cs$.

The shafts **219**, **178**, and **182** drive respectively the shafts **184**, **185**, and **186** respectively through the integrators **187**, **188**, and **189**. The integrators are connected for generation of logarithms. Then the motions of the shafts **184**, **185**, and **186** are respectively $\log W_B$, $\log s$ and $\log (r+cs)$.

The shafts **184** and **185** drive the shafts **190** and **191** respectively through the multipliers **192** and **193** of ratio equal to two. Thus the motions of the shafts **190** and **191** are respectively $2 \log W_B$ and $2 \log s$.

The shafts **190** and **191** drive the shaft **194** through the adder **195**. Thus the motion of the shaft **194** is: $2 \log W_B + 2 \log s$.

The shafts **194** and **186** drive the shaft **196** through the adder **197** working as a subtractor. Thus the motion of the shaft **196** is:

$$2 \log W_B + 2 \log s - \log (r+cs)$$

The shaft **196** drives the shaft **198** through the integrator **199** connected in such a manner that the input motion of the shaft **196** is the logarithm of the output motion of the shaft **198** which is then representative of

$$\frac{W_B^2 s^2}{r+cs}$$

because

$$\log \frac{W_B^2 s^2}{r+cs} = 2 \log W_B + 2 \log s - \log (r+cs)$$

It is desired to integrate the motion of the shaft **198** with respect to time. For this purpose a timing motor **201** drives the shaft **200**, the motion of which is then a uniform one.

The shafts **200** and **198** drive the shaft **202** through an integrator **203**. Thus the motion of the shaft **202** is

$$\int \frac{W_B^2 s^2}{r+cs} dT$$

i. e. the function B such as defined by the Equation 2. Referring to Fig. 2, the shaft **202** drives a hand **204** moving in front of a dial **205** on which the values of B are marked. Before starting drilling with a new bit the shaft **202** is turned to bring the hand **204** to zero position. Critical values of B for which different kinds and sizes of bits are dull are also marked on the dial **205**.

The computer described above performs automatically all the calculations according to Formulas 2 and 11. As stated above the rate of drilling *r* used for such a computation must be a true rate of drilling, i. e. the rate of progress with which the bit enters the formation, and not the rate of progress of the downward motion of the upper part of the drilling string visible above the earth surface. Without departing from the scope of the appended claims, the computation might also be done not with Formula 2 which is an integral, i. e. a sum of infinitely small increments, but with a sum of finite increments. In such case different factors of the formula must be replaced as follows: dT per ΔT which is an increment such as 5 minutes for example.

W_B, *s* and *r* must be considered respectively as the average weight on bit, rotary angular velocity, and rate of drilling during the time interval ΔT. And the average rate of drilling is approximately the same when considering the rate of progress of the bit or the rate of progress of the upper portion of the drilling string. Consequently, the average rate of drilling is the progress of the downwards motion of the kelly during the time interval ΔT.

Various other alterations and changes may be made in the formula used for computation which general form is the relationship (1), in form and arrangement of the details of the described apparatus without departing from the scope of the appended claims.

What I claim and desire to secure by Letters Patent is:

1. Apparatus for indicating the degree of wear of a rotating bit attached to a rotary drilling string, comprising means for providing a signal representing the rate of downward progress of the bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit, a computer for combining said signals to produce a resultant signal representing the quotient of said second signal over said first signal, said resultant signal representing the rate of wear of the bit and varying with time, said computer including an integrator for inte-

grating said resultant signal with respect to time.

2. In an arrangement for rotary drilling employing a drilling string having a bit attached thereto and comprising a means cooperating with said drilling string for producing a signal representing the rate of downward progress of the bit, means responsive to said signal for producing another signal that decreases with the increase of said first signal and an integrator operated in a definite relationship to an independent variable progressively increasing with time for integrating said other signal with respect to said independent variable to obtain a measurement of the degree of wear of the bit.

3. In an arrangement for rotary drilling employing a drilling string having a bit attached thereto and comprising a means cooperating with said drilling string for producing a signal the magnitude of which varies substantially in an inverse proportional relationship to the rate of downward progress of said bit, and a time driven mechanism responsive to said signal for integrating said varying magnitude with respect to time to obtain a measurement of the degree of wear of the bit.

4. In an arrangement for rotary drilling employing a drilling string having a bit attached thereto and comprising an independent means cooperating with said drilling string for producing a signal representing the rate of downward progress of said bit, another independent means for producing a signal representing a function of the weight applied to the bit, means responsive to said two signals for producing a resultant signal that increases with the decrease of said first signal and that increases with the increase of said second signal in accordance with a predetermined relationship and an integrator for integrating said resultant signal with respect to time to obtain a measurement of the degree of wear of the bit.

5. In an arrangement for rotary drilling employing a drilling string having a bit attached thereto and comprising a rate responsive means for producing a signal representing the rate of downward progress of said bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit, a computer responsive to said two signals for producing a resultant signal that represents substantially a quotient obtained from dividing the magnitude representing a function of said weight over a magnitude representing said rate of progress, said computer comprising a time driven mechanism responsive to said resultant signal for integrating said resultant signal with respect to a variable that progressively increases with time to obtain a measurement of the degree of wear of the bit.

6. In an arrangement for rotary drilling employing a drilling string having a bit attached thereto and comprising a rate responsive means for producing a signal representing the rate R of the downward progress of said bit, a weight responsive means for producing a signal representing a function of the weight W applied to the bit, means for producing a signal representing the number of revolutions s of said bit per unit of time, a computer mechanism responsive to said three signals for producing a resultant signal representing the value

$$\frac{W^a S^b}{R^d + CS}$$

where a, b, c, and d are suitably chosen constants, said computer including an integrator responsive to said resultant signal for integrating said resultant signal with respect to time.

7. Apparatus for indicating the degree of wear of a rotating bit attached to a rotary drilling string, comprising means for providing a signal representing the rate of the downward progress of the bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit, means responsive to said signals for producing a resultant signal representing the rate of wear of the bit, said resultant signal varying with respect to an independent variable that progressively increases with time, and an integrator for integrating said resultant signal with respect to said variable.

8. In an arrangement for rotary drilling employing a drilling string having a bit attached thereto and comprising a rate responsive means for producing a signal representing the rate of the downward progress of said bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit; means for producing a signal representing the angular velocity of said bit, means responsive to said three signals for producing a resultant signal representing the rate of wear of said bit, and an integrator for integrating said resultant signal with respect to time.

9. Apparatus for indicating the degree of wear of a rotating bit attached to a rotary drilling string, comprising means for providing a signal representing the rate of the downward progress of the bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit, means for producing a signal representing the angular velocity of the bit, means responsive to said signals for producing a resultant signal representing the rate of wear of the bit, said resultant signal increasing with the increase of said second signal and decreasing with the increase of said first signal, and an integrator for integrating said resultant signal with respect to time.

10. Apparatus for indicating the degree of wear of a rotating bit attached to a rotary drilling string comprising means for providing a signal representing the downward progress of the bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit, means for producing a signal representing the angular velocity of the bit, means for combining said second and third signals into a resultant signal, means responsive to said resultant signal and said first signal for producing a signal representing the quotient of said resultant signal over said first signal, said quotient representing the rate of wear of said bit, and an integrator for integrating said quotient representing signal with respect to time.

11. Apparatus for indicating the degree of wear of a rotating bit attached to a rotary drilling string comprising means for providing a signal representing the rate of downward progress of the bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit, means for producing a signal representing the angular velocity of the bit, means for combining said first and third signals into a resultant signal, means responsive to said second signal and said resultant signal for producing a signal representing the quotient of said second signal over said resultant signal, said quotient representing the rate of wear of said bit and an integrator for integrating said quotient representing signal with respect to time.

12. Apparatus for indicating the degree of wear of a rotating bit attached to a rotary drilling string, comprising means for providing a signal representing the rate of the downward progress of the bit, a weight responsive means for producing a signal representing a function of the weight applied to the bit, means for producing a signal representing the angular velocity of the bit, means for combining the first and third signals into a resultant signal, means for combining the second and third signals into a resultant signal, means responsive to said two resultant signals for producing a signal representing a quotient of said second resultant signal over said first resultant signal, said quotient representing the rate of wear of said bit, and an integrator for integrating said quotient representing signal with respect to time.

ARTHUR LUBINSKI.

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