Oct. 29, 1968 F. H. REDWINE ET AL 3,408,561

FORMATION RESISTIVITY MEASUREMENT WHILE DRILLING UTILIZING PHYSICAL CONDITIONS REPRESENTATIVE OF THE SIGNALS FROM A TOROIDAL COIL LOCATED ADJACENT THE DRILLING BIT

Filed July 29, 1963

5 Sheets-Sheet 1

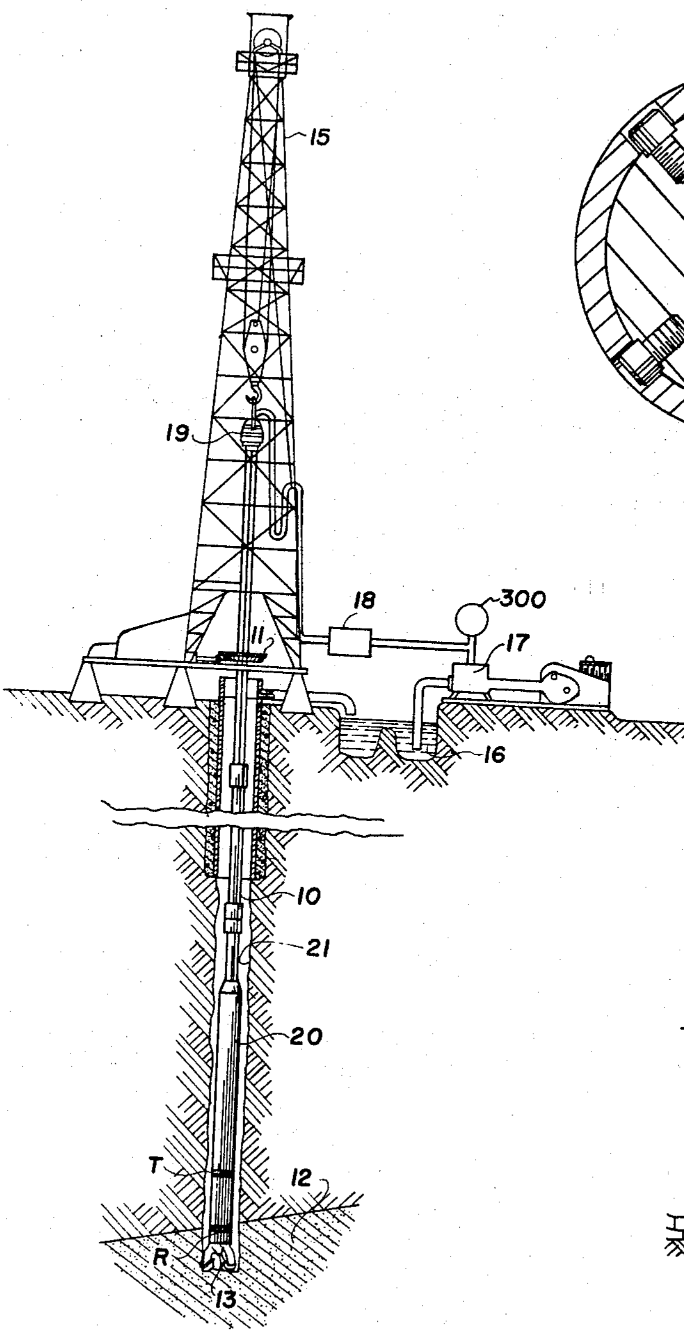

FIG. 1

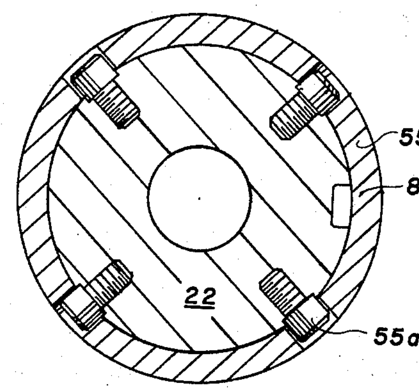

FIG. 4

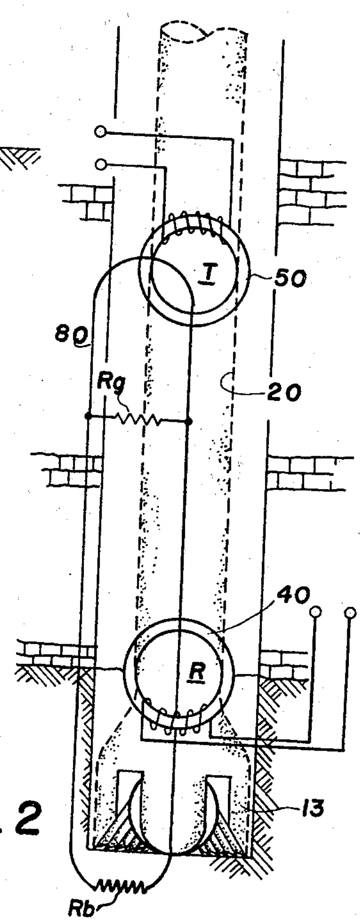

FIG. 2

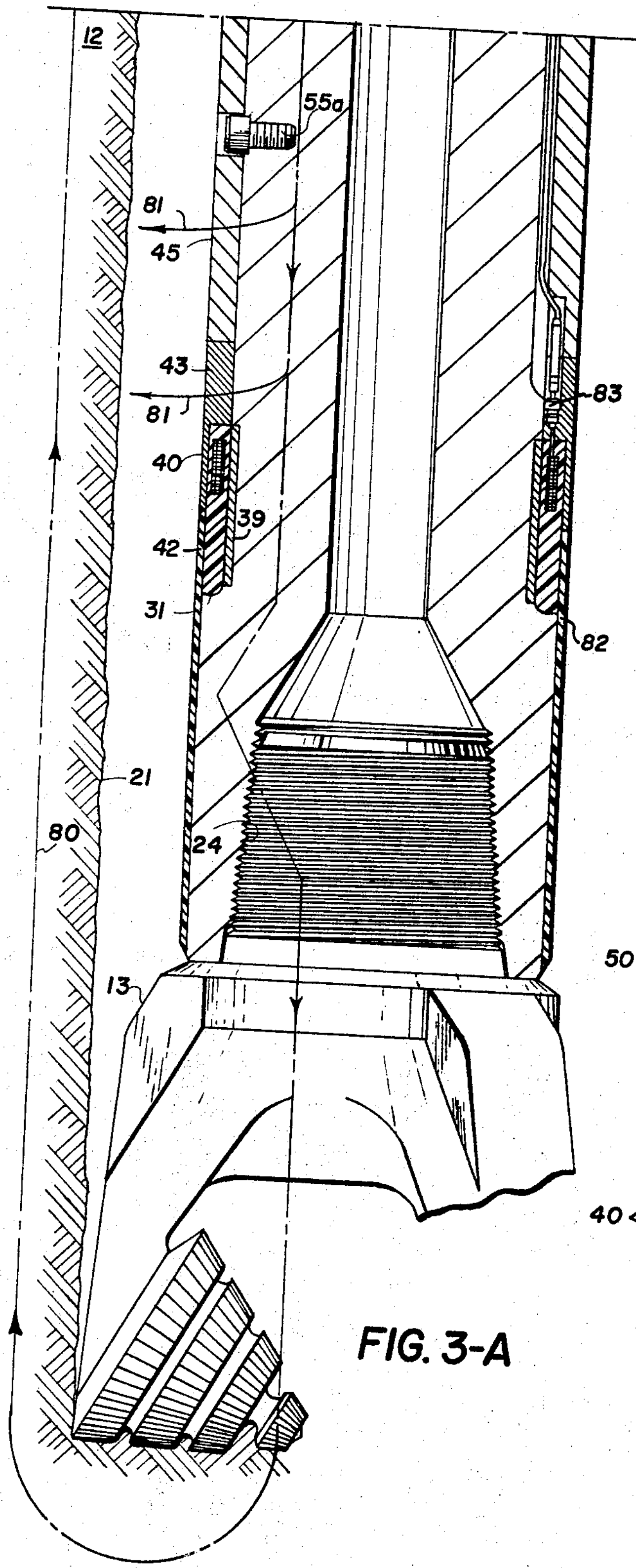
12
55a
81
45
43
81
40
39
42
31
83
82
21
80
24
13

FIG. 3-A

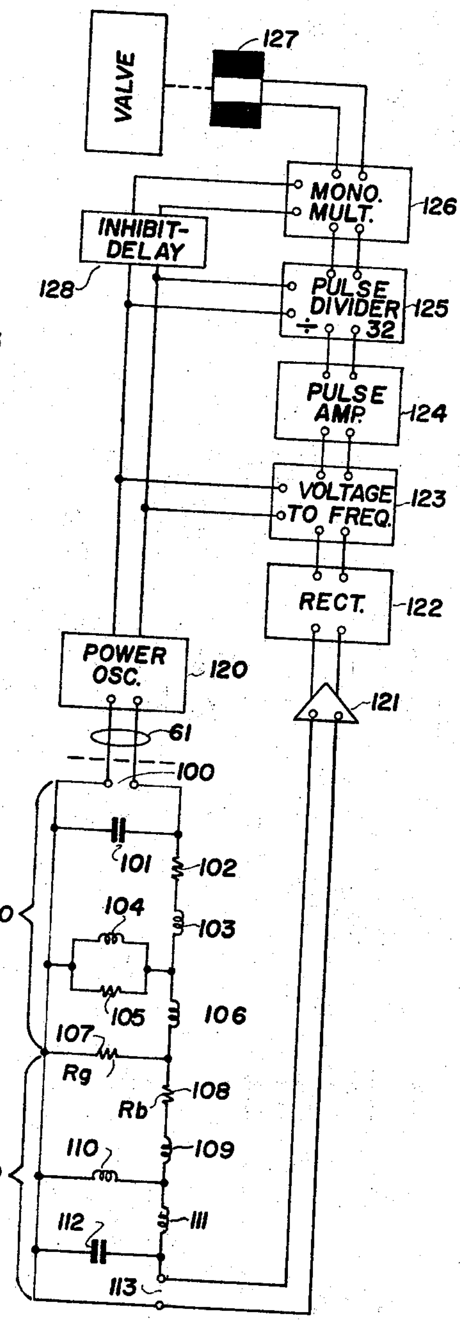
VALVE
127
MONO. MULT.
126
INHIBIT-DELAY
128
PULSE DIVIDER ÷ 32
125
PULSE AMP.
124
VOLTAGE TO FREQ.
123
RECT.
122
POWER OSC.
120
121
61
100
101
102
104
103
50
105
106
107
Rg
108
Rb
110
109
40
112
111
113

FIG. 5

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FORMATION RESISTIVITY MEASUREMENT WHILE DRILLING UTILIZING PHYSICAL CONDITIONS REPRESENTATIVE OF THE SIGNALS FROM A TOROIDAL COIL LOCATED ADJACENT THE DRILLING BIT

Filed July 29, 1963

5 Sheets-Sheet 3

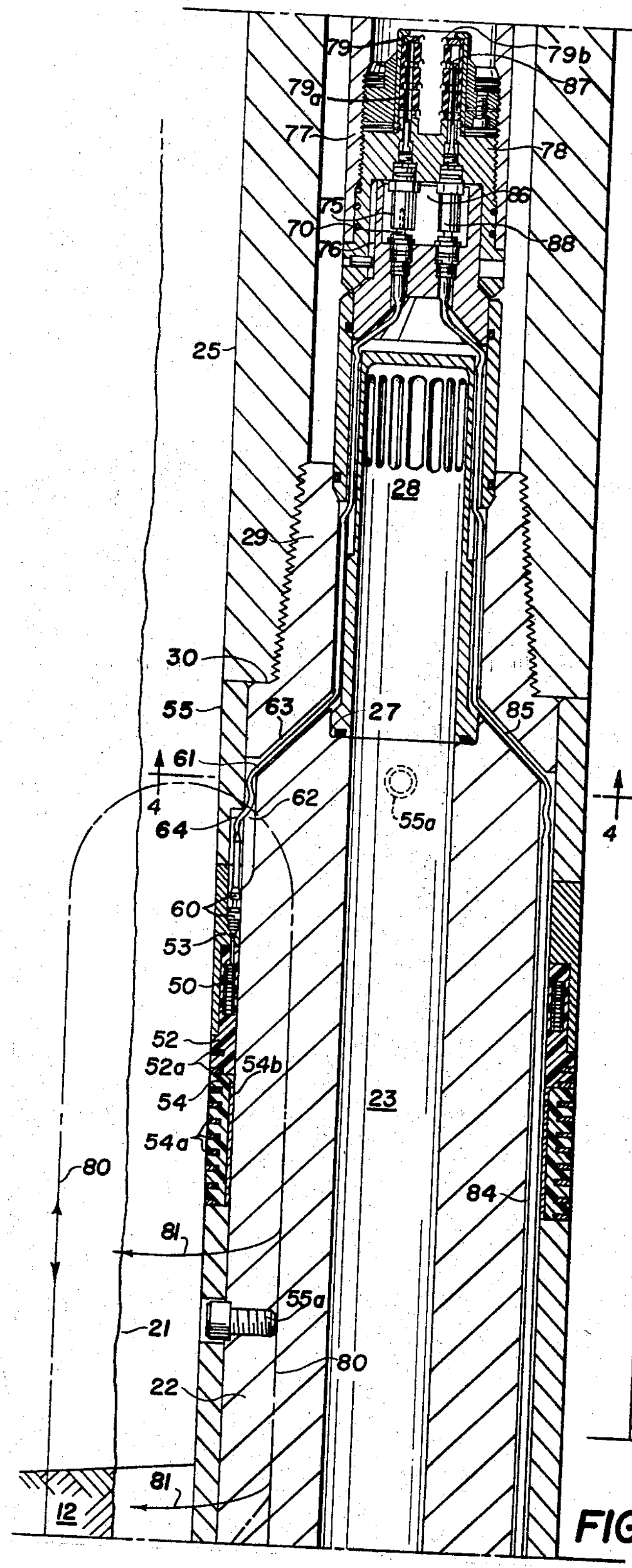

FIG. 3-B

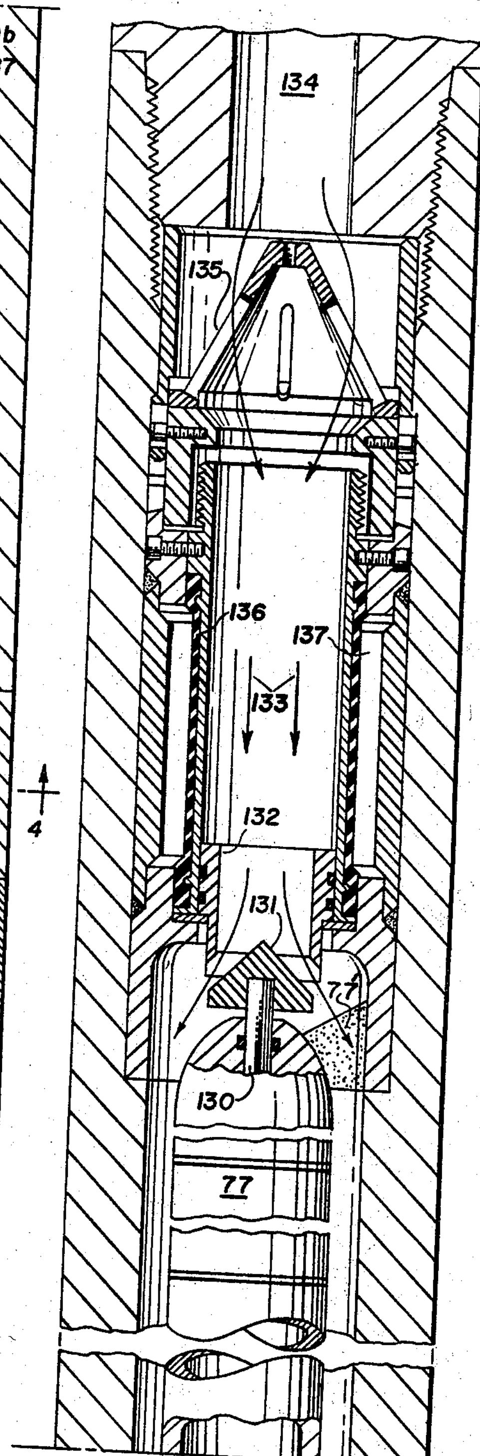

FIG. 3-C

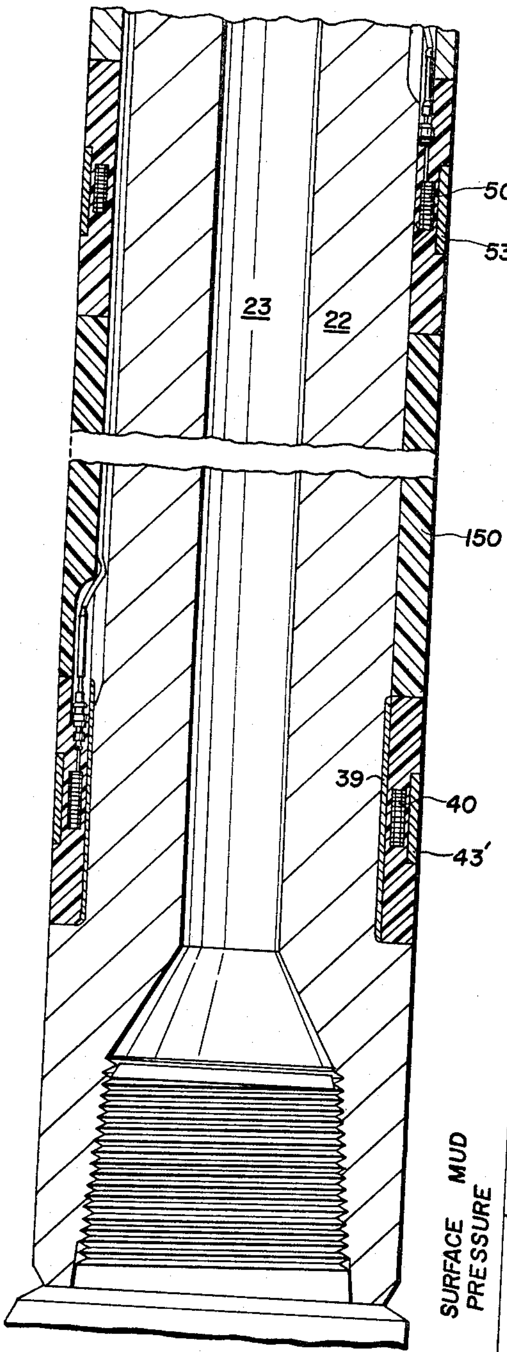

FIG. 7

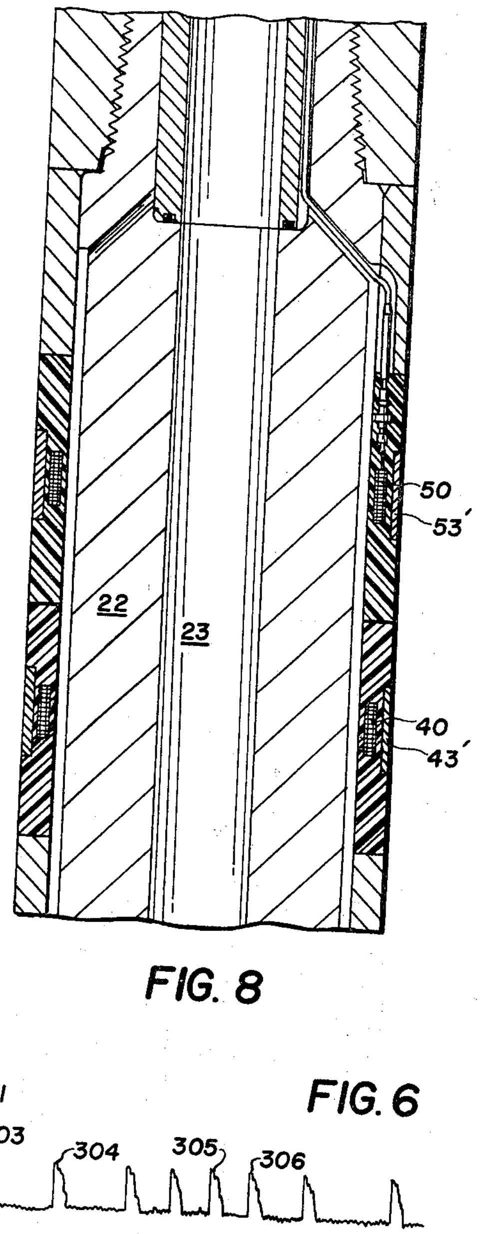

FIG. 8

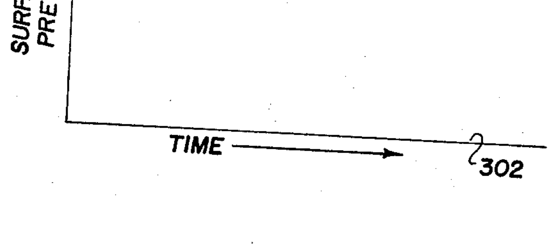

FIG. 6

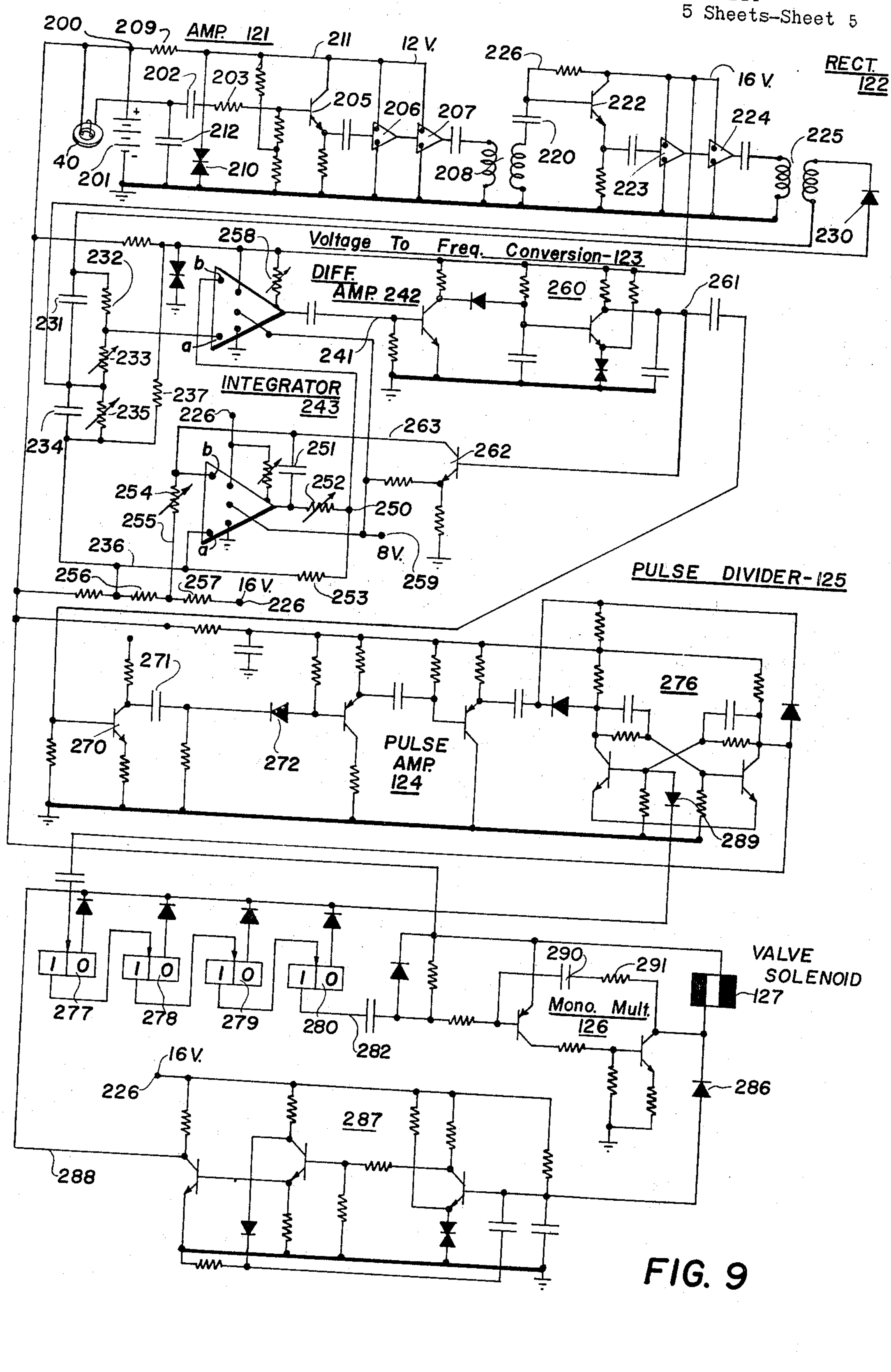
AMP. 121
12 V.
16 V.
RECT. 122
Voltage To Freq. Conversion-123
DIFF. AMP. 242
INTEGRATOR 243
8V.
PULSE DIVIDER-125
PULSE AMP. 124
VALVE SOLENOID
Mono. Mult. 126

FIG. 9

United States Patent Office

3,408,561

Patented Oct. 29, 1968

3,408,561

FORMATION RESISTIVITY MEASUREMENT WHILE DRILLING, UTILIZING PHYSICAL CONDITIONS REPRESENTATIVE OF THE SIGNALS FROM A TOROIDAL COIL LOCATED ADJACENT THE DRILLING BIT

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Filed July 29, 1963, Ser. No. 298,298
14 Claims. (Cl. 324—6)

This invention relates to well logging and has particular application to systems for determining properties or characteristics of earth formations in a well while such a well is being drilled.

Various systems have been proposed or have been employed in the past for logging a well to determine one or more characteristics of the formation being penetrated by the bit while the well is being drilled. In general, such methods of "logging while drilling" utilize a number of spaced electrodes placed near the lower end but insulated from the drill pipe string. In some systems the bit itself has been electrically insulated from the rest of the drill pipe so that current may be passed between the two electrically separate elements. Flow of such current is modified by the electrical resistivity of the earth formation near the drill bit.

Such systems share certain common disadvantages including, for example, the necessity for insulating electrically a section of the drill collar from the rest of the drill string. During the process of drilling, the whole string is constantly being subjected to violent shocks in tension, compression and shear which must be transmitted mechanically through the insulation. Since insulating materials are relatively weak and more susceptible to fracture and fatigue than steel pipe, all such systems mechanically are unreliable in addition to being expensive to manufacture and maintain. Likewise, such systems share the disadvantage that the insulation, which is on the outside as well as on the inside of the drill collar, is exposed to abrasion and erosion by the drilling fluid, making frequent and costly replacements of such insulation necessary.

In another system, such as disclosed in U.S. Patent No. 2,354,887, it was proposed to mount a toroid-shaped coil of wire, which is wound on a core of ferro-magnetic material which encircles the drill collar near the drill bit, in such a way that the axis of the toroid is parallel to and preferably coincides with the axis of the drill collar. It was expected that the impedance of such a coil would be affected sufficiently by the impedance of the electric path of its one-turn secondary winding consisting of the drill pipe, the formation near the drill bit and its return path through the earth, to produce a usable measurement of formation resistance at the drill bit. However, it has been found that the variations in the electrical resistance of the formation near the bit in the normal range of such values do not alter the impedance of the coil sufficiently to make meaningful measurements possible. It is the purpose of the present invention to overcome difficulties, such as the foregoing, through the use of a separate detector coil, preferably near the bit. The voltage induced in such detector coil essentially will be proportional to the conductivity of the formation near the drill bit.

It is a further object of this invention to provide a section of pipe between a transmitter coil and a detector coil through which part of the current will pass into the formation in a predominantly horizontal direction, thus forcing the remainder of the current through the detector coil and the drill bit at the contact between the drill bit and the bottom of the borehole.

In accordance with the present invention, there is provided a transmitting toroid mounted on the outer wall of a drill stem at a point spaced above a drill bit. A receiving toroid is mounted on the drill stem preferably immediately adjacent to the bit. An alternating current source mounted in the drill stem is connected to the transmitting toroid for induction of alternating current flow longitudinally through the bit to the formation at the bit-formation contact. Means connected to the receiving toroid translate induced voltages into pressure pulsations in the mud stream flowing through the drill stem for telemetering resistivity information to the earth's surface.

In a preferred embodiment, the transmitter and receiver are mounted at spaced points along a drill sub adjacent a drill bit. The transmitter and receiver are each mounted in insulating bodies which encircle the sub with protective shrouds extending over both the transmitter and the receiver with a non-conductive zone in the surface of the sub to promote current flow through the bit to the earth's formation.

For a more complete understanding of the present invention and for further objects and advantages thereof, reference may now be had to the following description taken in conjunction with the accompanying drawings in which:

FIGURE 1 is an elevational view of a well showing the borehole in section;

FIGURE 2 schematically illustrates the measuring circuit employed in FIGURE 1;

FIGURES 3A–3C are sectional views of a sensing sub constructed in accordance with the invention;

FIGURE 4 is a sectional view taken along line 4—4 of FIGURE 3B;

FIGURE 5 shows the electrical network of the invention in block form;

FIGURE 6 illustrates time pulse modulation employed in the invention;

FIGURE 7 is a modification of the system of FIGURE 3B employing an insulating spacer;

FIGURE 8 is a further modication in which a transmitter and receiver are closely coupled; and

FIGURE 9 is a circuit diagram of a down hole portion of the system.

In FIGURE 1, a drilling system is shown in which a drill stem **10** is driven by a rotary table **11** for penetration of a formation **12** by a bit **13**. The bit **13** is connected to the drill stem **10** by a sub **20**. The drill stem is supported by conventional draw works in a derrick **15**. Drilling mud from a slush pit **16** is forced through the drill stem **10** by a mud pump **17** and passes through a detector **18** and a hose leading to a swivel **19**. It is the purpose of the present invention to provide for continuous measurement at the earth's surface of the resistivity of the formation **12** including formations as they are newly exposed by the bit **13**. The measurement of the formation resistivity prior to invasion by drilling fluids is highly desirable in the interpretation of the stratigraphy through which the resultant borehole **21** passes and, thus, the successful measurement of resistivity as drilling progresses is highly valuable.

In accordance with the present invention, pressure pulses are generated in the mud stream flowing down through the drill stem **10** by a mechanism contained in sub **20**. The repetition rate of the pressure pulses transmitted to the surface is continuously measured as will hereinafter be described, the pulses being sensed by detector **18** and recorded as a function of time or as a function of the depth of the bit **13**. A continuous log may thus be produced during the drilling operation. The instrumentalities employed for utilization of the energy of the mud stream for production of the pressure pulses in general are known. Representative of prior art methods and systems for telemetering by way of the mud streams are Patent Nos. 2,524,031, 2,658,284 and 2,659,-046 to J. J. Arps and Patent No. 2,898,088 to Alder.

FIGURE 2 schematically represents operations of the present invention wherein the sub 20, shown dotted, is coupled at the lower end thereof to the bit 13. A transmitting toroid 50 encircles the sub 20 at a point spaced above the bit 13. A receiving toroid 40 encircles the sub 20 immediately adjacent to the bit 13. Current flow along a path represented by the loop 80 is established by flow of alternating current in the winding of the transmitter 50. Since the sub 20 is conductive, some of the current may leak from the conductive body of the sub to the adjacent formations along a path, the resistivity of which is represented in FIGURE 2 by the legend R_g. The path from the sub 20 to the formations, which includes the bit 13, will be of resistance R_b which will vary in dependence upon the resistivity of the newly exposed formation. Thus, the formation resistivity R_b of FIGURE 2 will control the flow of current through receiver 40. It is the variations of resistivity R_b which are of primary interest in the present invention. Variations in the current linked to the receiver 40 induce voltages in receiver 40 which appear at the output terminals of the winding and which will be employed for sending impulses to the earth's surface which are representative of such variations.

One embodiment of the system of the present invention is illustrated in FIGURES 3A–3C. Where consistent, like parts have been given the same reference in FIGURES 3A–3C as in FIGURES 1 and 2.

Sub 20, in FIGURES 3A and 3B, comprises a central mandrel 22 having a central flow channel 23 extending downwardly to the threaded coupling leading to bit 13. The threaded pin of bit 13 is served into the box 24. The pin on the upper end of the mandrel 22 is threadedly secured to an upper section 25 and has a cylindrically re-entrant opening 27 to receive the lower end of a flow crossover element 28 which extends upward into an instrument housing in the upper section 25.

Mandrel 22 of sub 20 is a heavy-walled steel drill collar, reduced in diameter from its upper shoulder 30 to the lower shoulder 31 adjacent to the coupling 24. A short insulating cylinder 42 of insulating character is mounted at the lower end of sub 20. The outside diameter of the cylinder 42 corresponds generally with the maximum diameter of the sub 20. Receiver 40 is embedded in cylinder 42. Receiver 40 is a detecting coil for measurement of formation resistivity. A steel band 43 has a cylindrical extension which enshrouds the receiver 40, protecting the same against abrasion. The outside diameter of the band 43 preferably corresponds with the diameter of the sub 20.

A spacer cylinder 45 is telescoped onto the mandrel 22 and is secured thereto by suitable studs 55*a* extending through the cylinder 45. A transmitter 50 is embedded in a second short insulating cylinder 52 which is positioned on top of an insulating cylinder 54. A steel spacer 53 is positioned above the insulating cylinder 52 and includes a cylindrical extension which enshrouds the transmitter 50. A pair of steel rings 52*a* are mounted in the lower end of the insulating cylinder 52. A plurality of steel rings 54*a* are mounted in the insulating cylinder 54. Rings 52*a* and 54*a* are of diameter corresponding with the outer diameter of the sub 20. They are cast in insulating material, such as an epoxy resin, so that they will provide protection against abrasion while being maintained electrically insulated one from the other and from mandrel 22. The ring 54 initially is cast on a metallic supporting cylinder 54*b*. The cylinder 54*b* encircles the reduced diameter portion of the mandrel 22. It will be noted that the transmitting toroid is embedded within the insulating material of the cylinder 52. A short spacer cylinder 55 is then secured to the mandrel 22 above the transmitting toroid 50 with the upper end of cylinder 55 coinciding with shoulder 30.

As illustrated in the sectional view of FIGURE 4, the cylinder 55 is secured to the mandrel 22 by four studs 55*a*. Cylinder 45 is similarly secured by studs 55*a* to mandrel 22. The spacers 45 and 55 provide a measure of mechanical shielding for the non-conductive cylinders 42 and 52 and, along with the bands 43 and 53, provide protection for the receiver 40 and the transmitter 50. A ring 39 of high magnetic reluctance such as copper is mounted beneath the toroid 40. Ring 39 provides a measure of magnetic shielding for receiver 40.

In the embodiment illustrated in FIGURES 3A–3C, a circuit is provided which includes the transmitter 50. Connections are completed by way of a plug unit 60 and a cable 61. The plug unit 60 is positioned in a recess in the inner wall of the spacer 53. The mandrel 22 has a groove 62 in the wall thereof extending from a hole or channel, to a point adjacent to the upper end of the plug unit 60. One terminal of the coil of transmitter 50 is thus electrically connected through cable 61 to a plug 70 mounted in the upper end of the flow crossover unit 28. The other terminal of transmitter 50 is connected to the sub which is at ground potential. The crossover unit 28 has an isolation channel for passage therethrough of the cable 61 and is secured to the upper end of male coupling 29 by means such as suitable set screws, not shown. The plug 70 mates with a plug 75 which is located in a recess 76 in the bottom of an instrument housing 77.

Plug 75 is one of four plugs mounted in the recess 86 in the bottom end of a high pressure bulkhead 78. Bulkhead 78 is threaded into the lower end of the instrument housing 77. Four conductive rings, such as ring 79, are mounted one above the other to form a cylindrical extenison of the bulkhead 78. As illustrated. the plug 75 is connected by way of a wire 79*a* to the upper ring 79. The ring 79 has a resilient, inwardly directed contact 79*b* which is adapted to make contact with a conductive segment on a male insert, not shown, to be centrally located within the housing 77. Ring 79 and the remaining three rings are insulated from each other and from the housing in which they are fitted. It will be noted that the plug at the end of cable 85 is connected to the second ring 87 by a suitable wire by way of plug 88. The remaining two plugs in the recess 76 serve to complete circuits leading to ground. Thus, the plug 70 completes the ungrounded side of the circuit for the transmitter 50. The plug 88 serves to complete the ungrounded side of the circuit for the receiver 40. The transmitter 50 is energized from an A.C. source in housing 77 by way of plug 75. The detected signal from receiver 40 is applied to the instrumentation in housing 77 by way of plug 88.

When energized, transmitter 50 produces a magnetic field. Electrical currents are induced in the sub 22 which is a part of the single-turn current loop 80 coupled to the transmitter.

The loop 80 is diagrammatically represented in FIGURES 3A and 3B by the dashed line. The loop 80 includes the portion of the current path flowing in the mandrel 22 and the drill bit 13. Primary flow between the drill stem and the formation below the transmitter is through the teeth of the drill bit to the newly exposed formations over which the teeth ride. Current may leak directly to the borehole wall from the spacer 45 as indicated by arrows 81. Most of the leakage current passes through the mud column from the spacer 45 and thence through the formation.

The current loop is closed above the transmitter 50 by return flow to the sub 20 and to the drill stem above the sub. The leakage current represented by arrows 81 acts as a current sheath or guard so that current flowing from bit 13 is forced to return through the earth well beyond the wall of the borehole.

Since the resistance through the earth back to the drill stem and through the drill stem itself is very low compared with the resistance at the bit, measurement of bit current is essentially a function of the formation resistance at the bit.

As illustrated in FIGURE 3A, the receiver **40** is positioned as close as possible to the bit **13** so that substantially all of the current linked to the receiver **40** passes into the formation at the bit contact. The progressive exposure of new formations by the bit is accompanied by the measurement of resistivity since, as above noted, the primary variable in the current loop **80** is represented by the bit-formation contact. The flow of current through the section of the mandrel **22** and the spacer **45** between transmitter **50** and receiver **40** effectively forms a current guard permitting a more precise measurement of uninvaded formation resistivity by reason of the limited linkage to receiver **40**.

Arrows **81** represent the flow of current from the sub **20**. In a preferred embodiment, the outer wall of the sub **20** below the receiver **40** is covered with an insulating sleeve **82**. Sleeve **82** prevents current linked to the receiver from flowing through points other than the bit-formation contact. Thus a guard above the receiver forces the bit current to travel in the formation well behind the borehole wall. The sleeve **82** prevents flow of receiver-coupled current except through the bit-formation contact.

Electrically the system may be represented by the equivalent circuit shown in FIGURE 5. The driving voltage is applied by way of cable **61** to the transmitter **50** at input terminals **100**. The condenser **101** represents the shunt capacitance of the transmitter **50**. Resistance **102** is the resistance of the winding of the transmitter **50**. Further, as to the transmitter **50**, inductance **103** is the leakage inductance; inductance **104** is the primary inductance; resistance **105** is the equivalent core loss resistance; and inductance **106** is the secondary leakage inductance.

Resistance **107** is the resistance in the path of the guard current. Resistance **108** is the apparent formation resistance in the loop **80**.

As to receiver **40**, the inductance **109** is the primary leakage inductance; inductance **110** is the primary inductance; inductance **111** is the secondary inductance; and capacitance **112** is the shunt capacitance.

The voltage induced in receiver **40** appears at output terminals **113**. The latter terminals include a plug unit **83** which is shown in FIGURE 3A. A cable extends upwardly through a channel **84** and through a port **85** in the crossover unit **28**. The cable from the receiver **40** extends to plug **88** located in the recess **86** for application of the voltage induced in receiver **40** to a circuit in the housing **77**.

By a proper selection of the parameters of transmitter **50** and receiver **40**, it is possible to hold the voltage at terminals **113** relatively constant even though the resistance R_g of the leakage path as represented by resistance **107** of FIGURE 5 varies over a wide range. Such condition is highly desirable in order that the output voltage from receiver **40** will be representative of formation resistivity. It can be shown that the current linked to the receiver **40** may be such that it varies primarily in accordance with the bit-formation resistance.

In a preferred mode of operation, the voltage represented by current flow through the leakage resistance **107** will be kept constant by making the coupling coefficient between the transmitter **50** and the receiver **40** as large as possible while maintaining the inductance of the transmitter and receiver relatively small.

FIGURE 5, in block form, illustrates the relation between system components employed for excitation of the transmitter **50** and for utilization of the voltage induced in the receiver **40**. An alternating current oscillator **120** is connected to the input terminal **100** of the transmitter **50**. The output terminals **113** of the receiver **40** are connected to a high impedance amplifier **121** whose output is applied to a rectifier **122**. The rectified voltage is then applied to a frequency converter **123** to produce output pulses at a rate proportional to the magnitude of the voltage from rectifier **122**. The output of the converter **123** is applied by way of an amplifier **124** to a dividing network **125** whose output is a low-frequency, time-spaced pulse train.

The time interval between pulses is to be measured at the earth's surface. For this purpose, the output from the pulse divider **125** is applied to a monostable multivibrator **126** having a solenoid **127** connected in one side thereof. The solenoid **127** serves to control the valve in the stream of drilling fluid flowing through the instrument housing **77** for abruptly changing the resistance to flow. Such abrupt changes result in pressure pulses which are propagated up the drill stem **10** to the surface where they are sensed by the detector unit **18**. From the latter unit resistivity data is applied to a recording unit where it is registered either as a function of time or as a function of depth.

An embodiment of a valving system in simplified form is shown in FIGURE 3C. The instrument housing **77** includes the electrical units **121–128** of FIGURE 5 with the solenoid **127** adapted to actuate a shaft **130** which supports a valve element **131**. The valve element **131** extends into an orifice in a spout **132**. By varying the position of the valve element **131**, the impedance to fluid flow, as represented by the arrows **133**, may be changed. Abrupt variations in the flow impedance are propagated up the mud stream through the central channel **134** to the earth's surface where they are detected. A screen unit **135** is positioned at the lower end of the channel **134** and above the valve unit **131** to minimize the possibility of clogging the valve in its operation.

Only a portion of the valve system is shown in FIGURE 3C. Included is an upstream bladder **136** positioned above the valve element **131**. The instrument housing **77** included a hydraulic drive system for shaft **130** which is responsive to actuation of the valve solenoid **137**. In addition, a downstream bladder (not shown) is employed to sense downstream pressure. Control of the valve element **131** is accomplished through the use of the bladder **136** and the other elements above mentioned to convert signals applied to terminals **113**, representative of resistivity, into pressure pulses. A suitable valving system is illustrated and described in Patent No. 2,898,088 to Alder. In a preferred embodiment, the valving system is actuated primarily by energy in the mud stream with the solenoid **127** serving merely to control the valve action at low power level. For this purpose, a chamber **137** is provided behind the bladder **136** with the wall inside the bladder **136** being perforated in order to introduce pressure variations into the chamber **137**. The operation is such that the valve element **131** changes from one position to another for predetermined time intervals to introduce pressure variations in the mud stream which are of square wave character. Since the system operates in response to energy from the mud stream and involves a hydraulic system which requires recovery time, an inhibit-delay unit **128** is connected between the output of the multivibrator **126** and the output of the pulse divider **125** to prevent the divider **125** from responding to input pulses thereto. A fixed delay is imposed on the system by unit **128** to permit the valve system to recover following each pulse. The delay, thus introduced, is compensated at the surface so that the rate of pulses appearing at the surface when modified to accommodate the delay is representative of resistivity at the bit-formation contact.

In accordance with the invention thus far described, alternating current induced in sub **20** flows vertically along the sub through the bit and vertically through the formations with the primary resistance being that identified with the bit-formation contact. The transmitter **50** is spaced a substantial distance from the receiver **40**. Receiver **40** is preferably mounted as close to the bit as is possible in order that all of the current linked to the receiver **40** will flow through the bit-formation contact with a minimum of leakage. The spacer **45** is employed to enhance to a degree leakage of current above the receiver **40**.

In contrast with the foregoing, a modification is illustrated in FIGURE 7 where the receiver **40** is spaced from the transmitter **50** in the same manner as in FIGURES 3A–3C, except for the fact that the spacer positioned between them and identified as spacer **150** is of insulating character, thus preventing the leakage of any current in that portion of the sub **20** between the transmitter **50** and the receiver **40**. In all other respects, the embodiment of FIGURE 7 is the same as the embodiment of FIGURES 3A–3C.

A further embodiment of the invention is illustrated in FIGURE 8, wherein the transmitter **50** and the receiver **40** are mounted immediately adjacent to one another so that a close, tight coupling factor is effective therebetween. In both FIGURES 7 and 8, the receiver **40** is shielded by a band **43'**. The transmitter **50** is shielded by a band **53'**. In FIGURE 8, transmitter **50** and receiver **40** are illustrated near the upper end of the sub **20**. In practice, they may be located near the bit or may be located at a point substantially above the bit, depending upon the particular measurement for which the system is to be employed. In FIGURES 7 and 8, much of the detail has been omitted because of the identity thereof with the structure of FIGURES 3A–3C.

FIGURE 9 illustrates, in detail, the circuit diagram which is shown in block form in FIGURE 5. While not shown, a power oscillator is employed to energize the transmitting toroid. In one embodiment of the invention, the transmitter was operated at a level of about 25 milliwatts at a frequency of 500 cycles per second. The input impedance to the transmitter **50** was about 5000 ohms. The transmitter **50** is thus linked by a current loop to the receiver **40**.

It will be noted that the receiver **40** is connected at one terminal to the positive terminal **200** of a battery **201**. The negative terminal of battery **201** is connected to ground. The other terminal of receiver **40** is connected by way of a condenser **202** and resistor **203** to the input of an amplifier **121** having three emitter-follower stages **205**, **206** and **207**, which feed a transformer **208** at the output of follower **207**. The amplifier **121** is supplied from battery terminal **200** by way of a resistance **209** and a regulator **210** comprised of Zener diodes which maintain the bus **211** at a potential of 12 volts above ground. Thus regulated, the amplifier **121** provides a gain of about 10 as between the input and the voltage from the transformer **208**.

A condenser **212** is connected in parallel with the receiver **40** to tune receiver **40** to the frequency of the oscillator **120**.

The secondary winding of transformer **208** is connected by way of condenser **220** to the second section of amplifier **121**. The second section includes three emitter-follower stages **222**, **223** and **224**. The output stage **224** feeds an output transformer **225**. The output section is supplied from a 16 volt bus **226** which is fed from battery **201**. A higher supply voltage is employed in the output section since the signal amplitude is somewhat greater than that which must be accommodated in the first section of amplifier **121**.

The signal from the secondary winding of transformer **225** is rectified in section **122** by the diode **230**. The voltage thus developed is applied to condenser **231**. The rectified signal voltage thus appearing across condenser **231** is employed in section **123** to produce output pulses which vary in their repetition rate in proportion to the magnitude of the voltage on condenser **231**. The latter pulses appear on the output bus **241** and are produced through the cooperative action of a differential amplifier circuit involving amplifier **242** and an integrated amplifier circuit involving the amplifier **243**.

The circuit leading from condenser **231** includes a voltage dividing network formed from resistors **232** and **233**. The juncture between resistors **232** and **233** is connected to input terminal *a* on the differential amplifier **242**. The resistor **233** is adjustable. The lower terminal of condenser **231** is connected by way of an RC biased network including condenser **234** and resistor **235**, which are connected in parallel, to a reduced voltage bus **236**. The lower terminal of condenser **231** is also connected by way of resistor **237** to the 16-volt bus **226**.

Amplifiers **242** and **243** in one form of the invention were Philbrick amplifiers Model PP65. The amplifier **242** serves as a differential amplifier, producing an output pulse each time the input voltage applied to the terminal *b* coincides with the voltage applied to terminal *a*. Amplifiers of the type above identified normally work with the operating voltages on the intermediate terminals at +15 volts, 0 volts and −15 volts, respectively. In the circuit illustrated in FIGURE 9, the upper terminal is connected to the 16-volt bus **226**. The center terminal is connected to an 8-volt bus **259**. The bottom terminal is connected to ground. Trimming resistors, such as resistor **258**, are provided to adjust the amplifier such that the output on bus **241** is balanced when terminals *a* and *b* are connected together.

Conduction in amplifier **242** is switched by application thereto by a control signal which is developed at terminal **250** by an integrator which embodies amplifier **243**. The integrator embodies condenser **251**. Condenser **251** is connected at one terminal to the 8-volt bus **236** by way of the voltage dividing network including resistors **252** and **253**. The juncture between resistors **252** and **253** is the output terminal of amplifier **243**. The second terminal of condenser **251** is connected by way of variable resistor **254** to a line **255**. Line **255** leads to a mid-tap on a voltage divider comprising resistors **256** and **257** which are connected in series between 16-volt bus **226** and the 8-volt bus **236**. The juncture between condenser **251** and resistor **254** is connected to the *b* input terminal of amplifier **243**. The *a* input terminal is connected to the 8-volt bus **236**.

In operation, the network including condenser **234** and resistor **235** serves to bias the output voltage from condenser **231** to 13 volts when the resistivity of the formations is very high such that zero voltage is induced in receiver **40**. Further, the voltage terminal **250**, normally at the start of each integrator cycle is at 13 volts. When the resistivity of the formations is of magnitude other than approaching infinity, there will be a time lag introduced by the operation of the integrator before the voltage at terminal **250** drops to the voltage equal to the signal voltage at terminal *a* of amplifier **242**. The integrator causes the voltage at terminal **250** to decrease linearly with time. At the instant that the integrator voltage equals the signal voltage, the amplifier **242** shifts in conduction, producing a positive voltage change at the output. This voltage output is then applied to a monostable multivibrator **260**, the output of which appears at terminal **261**. A reset circuit including transistor **262** is connected by way of conductor **263** to the *b* terminal of the amplifier **243**. The integrator is reset to carry out repeated comparison cycles.

A coupling circuit, including transistor **270**, is connected by way of condenser **271** and a diode **272** to a pulse amplifier **124** whose output drives a five stage divider **125**. Divider **125** is made up of five bistable multivibrators, **276**, **277**, **278**, **279** and **280**. Divider **125**, thus formed, produces one pulse on output line **282** for every 32 pulses appearing on the input line **241**.

The output line **282** is connected to a monostable multivibrator **126**. The monostable multivibrator **126** is connected to the valve operating solenoid **127** so that the valve element **131** of FIGURE 3C will be pulsed once for every 32 pulses generated by the conversion circuit **123**.

The output voltage from the multivibrator **126** is applied by way of diode **286** to a monostable multivibrator **287** which has a fixed delay. The output of the multivibrator **287** is connected to an inhibit bus **288** which in turn is connected by diodes, such as diode **289**, to each of the reset stages of the multivibrators **276–280**.

Multivibrator **126** includes a control circuit comprised of a condenser **290** and a resistor **291** which are adjusted so that multivibrator **126** has a period of three seconds.

Multivibrator **287** is pre-set to have a period of five seconds. By this means, the pulse divider **125** is disabled for eight seconds following each output pulse applied to the solenoid **127**. This provides a time-delay following each actuation of the valve **131** sufficient to permit the hydraulic system for valve **131** to recover so that it can be actuated upon the next succeeding pulse which appears after the expiration of the eight second delay period.

Briefly summarized, the system of FIGURE 9 operates as follows. The output from the receiver **40** is fed through three emitter-followers **205–207** and is then stepped up voltage-wise by a factor of approximately 10 through transformer **208**. This output is then fed through emitter-followers **222–224** and stepped up again by a factor of approximately 10 through transformer **225**. This signal is then rectified, providing an output of 30 volts D.C. for 1 ohm apparent resistance (R*b*). This D.C. voltage is inversely proportional to the apparent resistance through a range of at least 70 to 1. Any resistance over about 70 ohms produces a fall-off of the rectified voltage due to the voltage drop required to cause a conduction across the rectifying diode **230**.

In order to convert the D.C. voltage to a frequency, the integrator-level detector units are employed, utilizing two high-gain operational amplifiers **242** and **243**. One amplifier **242** is used in a differential amplifier mode as a level detector. In this application, whenever the two inputs *a* and *b* are of very nearly equal value, the output will swing through the full collector voltage. The second operational amplifier **243** is used as a linear integrator. The output of this linear integrator provides one input signal to the level detector, and the rectified voltage obtained from the emitter-follower section supplies the second input signal. Whenever the inputs are approximately the same (within a few millivolts), the output of the differential amplifier activates a monostable multivibrator **260**, which lasts about 25 milliseconds, resets the linear integrator through transistor **262** and initiates a new integration cycle. The output of multivibrator **260** is also fed to the emitter-followers that drive the divider **125**, the latter giving a division of 32. Using this system, the output pulse frequency is directly proportional to the apparent resistance of the formation.

In a particular circuit of the form illustrated, the output of integrator **243** varies from approximately +16 volts toward 0 volts in a linear manner at a negative slope of 3.56 volts per second. This linear output is divided down at point **250** to produce the voltage applied to the *a* input of differential amplifier **242**. Since E_{250} tends to be maintained at a common voltage of 8 volts, the equation describing the voltage applied to the *b* input of the differential amplifier is:

$$E_{242b}=13-t(2.22) \qquad (1)$$

where:

t is in seconds.

The voltage applied to the terminal *a* of the differential amplifier **242** is:

$$E_{242a}=13-\frac{5}{Rb} \qquad (2)$$

Since the differential amplifiers will switch when the two voltages are equal, the solution for t in terms of R*b* is:

$$t=\frac{2.25}{Rb} \qquad (3)$$

Since the integrator **243** is reset almost instantly and since the output pulses are applied to the divider **125**, a final output pulse period applied to the control solenoid is:

$$T=\frac{72}{Ra} \qquad (4)$$

Since depletion of the valve is to be avoided, an 8 second delay is incorporated which inhibits the divider **125** so that the final pulse period received at the surface is:

$$T=\frac{72}{Ra}+8 \qquad (5)$$

The surface equipment upon receipt of each pulse shuts down for a period of 8 seconds. Thus, there is obtained a frequency at the surface which is:

$$F=\frac{Ra}{72} \qquad (6)$$

The system has been found to operate over a range of 70/1. The actual limits as to the lowest resistivity measurement required are readily controlled by adjusting the resistor **203**. The lower limit of the apparent resistance that can be measured successfully appears to be around 0.1 ohm or less. Consequently, operation through a range of 0.1 ohm to 7 ohms or from 1 ohm to 70 ohms is accomplished with little difficulty. This is with a voltage of 2 volts (RMS) applied to the transmitter **50**. The actual power required by the oscillator may be less than 100 milliwatts. Most of the power in the entire system is used by the valve solenoid **127**, with the emitter-followers and other associated circuitry requiring nominally 400 milliwatts under quiescent conditions. The system requires a peak power of approximately 600–700 milliwatts when extremely low resistivities are encountered.

In the system of FIGURE 9, the voltage from battery **201** is normally 24 volts, being made up of 18 one and one-half volt mercury cells. When the transmitter is excited, the resistor **203** is adjusted such that for the minimum value of R*b* to be measured, the output voltage appearing across condenser **231** is equal to 30 volts. Resistor **233** is then adjusted such that the voltage across it equals 5 volts when the voltage across condenser **231** equals 30 volts. Resistor **235** is then adjusted such that the voltage across it equals 5 volts. Resistor **258** and the corresponding resistor for integrator **243** are adjusted such that the output voltage of each of the amplifiers is near +8 volts when both the *a* and the *b* input terminals are connected to a voltage source of 8.2 volts.

Resistor **254** is then adjusted such that the output of the integrator has a slope preferably of −3.55 volts per second. Resistor **252** is then adjusted such that the voltage across resistor **253** equals 5 volts when the output of the integrator amplifier **243** is at a maximum voltage.

In one embodiment of the invention toroids **40** and **50** were each formed with a core of tape-wound permalloy, a high quality magnetic material of 0.002 inch thickness and one and one-half (1½) inch width. Each core, when completed, had a thickness of the order of ⅛ inch to 3/16 inch and a diameter of the order of about 8 inches, the latter being determined by the size of the sub on which the toroid is mounted.

The transmitting toroid **50** was formed with a winding of 100 turns of No. 30 copper wire. The receiving toroid **40** including a winding of 1200 turns of No. 30 copper wire. The output power from the transmitter **50** was about 2 watts at 1 volt and 500 cycles per second.

In FIGURE 1 the surface detector system **300** may be of the type shown in Arps Patent No. 2,524,031 wherein compensation for the downhole valve recovery time (8 seconds in the embodiment described herein) is provided for recording a pulse train which is representative of formation resistivity.

In FIGURE 6 the response of the surface detector **300** of FIGURE 1 has been illustrated. The surface mud pressure is plotted along the ordinate **301** and time plotted as abcissa **302**. The relatively long period as between pulses **303** and **304** may represent low resistivity. The shorter interval as between pulses **305** and **306** may represent high resistivity. In practice, the pressure pulses appear distinctly above the noise in the mud stream as produced by the pump. They have been found to be clearly discernible above the noise and provide an accurate measure of resistivity.

The signal appearing at terminals **100** of FIGURE 5 which is proportional to the excitation of the transmitter **50** may be coupled to the signal appearing at the output terminals **113** of FIGURE 5 in a circuit which provides an output which is proportional to the ratio of the two signals. The output signal applied to the preamplifier **121** would then be proportional to the ratio of the input and output signals and would thus provide for compensation for variations in the system due to changes in temperature and the like.

Thus, the present invention involves a system for logging a well while drilling in which a drill string terminates in a sub having a bit at the end thereof. A transmitting toroidal coil encompasses the sub preferably at a point spaced above the bit. An elecrical source is connected to the coil for applying alternating current preferably at a predetermined level to produce an alternating magnetic flux. Alternating current is thus induced for flow through the drill sub and the bit. A receiver toroidal coil encompasses the sub immediately adjacent to the bit for detecting current flow to the formation from the bit. Preferably any wall portion of the sub below the receiver is covered with an insulating material so that current coupled to the receiver will flow to the formation through the bit. A signaling means is provided which is connected to the detecting coil for generating a physical condition detectable at the mouth of the well.

In one aspect of the invention, the condition is dependent upon the ratio of the reference voltage at the input to the transmitter and the output voltage at the terminals of the receiver. A system for obtaining such a ratio may be in accordance with well-known principles such as disclosed in the "Handbook of Automation Computation and Control" by Grabbe et al., John Wiley & Sons, Inc., 1959, at page 23–12, et seq. In a further aspect of the invention, the transmitter and receiver are mounted on the outer wall of the sub and are embedded in an insulating body. A protective metallic ring is provided for each of the transmitter and receiver to protect them against abrasion. The rings are so mounted as to prevent short circuits around the transmitter or receiver. In a preferred embodiment, exposed metallic walls in a sub between the transmitter and receiver permit current flow from the sub to adjacent formations to form a guard current which requires flow of bit current at substantial depths within the formation beyond the borehole walls.

Having described the invention in connection with certain specific embodiments thereof, it is to be understood that further modifications may now suggest themselves to those skilled in the art and it is intended to cover such modifictaions as fall within the scope of the appended claims.

What is claimed is:

1. In a well drilling system having means in a drill sub and bit at the bottom of said sub and a pressure pulse generator in the stream of drilling mud flowing to said bit, the combination which comprises:

(a) a transmitting toroid mounted in the outer wall of said sub at a point spaced above said bit,

(b) a receiving toroid mounted in the outer wall of said sub immediately adjacent to said bit,

(c) an alternating current source mounted in said sub connected to said transmitting toroid for applying alternating current at a predetermined level thereto to induce alternating current flow longitudinally through said sub and said bit and into the formation at the bit-formation contact,

(d) means housed within said sub for translating the voltage induced in said receiving toroid by said alternating current flow into time modulated electrical pulses, and

(e) means for applying said time modulated electrical pulses to said pressure pulse generator for transmission of time modulated pressure pulses to the earth's surface through said stream which are representative of the resistivity of the formations at the contact thereof with said bit.

2. A resistivity logging system which comprises the combination of:

(a) a drill collar adapted to receive a drill bit at the lower end thereof for contact with bottom hole formations,

(b) a first toroid encircling said drill collar immediately adjacent to said bit,

(c) a second toroid encircling said drill collar at a point spaced from said first toroid,

(d) means for energizing said second toroid with alternating current at a predetermined level for the production of current flow through said drill collar said first toroid and said bit into said formations at the bit-formation contact,

(e) generating means in said drill collar for producing pressure pulsations in the drilling fluid flowing to said formation through said bit for transmission to the earth's surface, and

(f) means coupled to said first toroid for energizing said generating means at a rate proportional to the magnitude of said current flowing through said bit-formation contact.

3. A system for logging a well while drilling which comprises:

(a) a drill collar having a bit at the end thereof,

(b) a toroidal coil encompassing said drill collar at a point spaced above said bit,

(c) an electrical source means connected to said coil for applying alternating current thereto at a predetermined level to produce magnetic flux within said coil to induce electrical current flow through said drill collar to said bit,

(d) a detector coil encompassing said drill collar immediately adjacent to said bit for detecting current flow from said bit to formations of varying resistivity exposed and contacted by said bit,

(e) signaling means connected to said detector coil for translating voltages induced therein by said current flow into physical conditions for transmission to and detectable at the mouth of said well, and

(f) means in the region of said mouth for sensing and recording said conditions as a function of the depth of said bit in said well.

4. An instrument sub for logging formation resistivity while drilling which comprises:

(a) an elongated sub adapted to receive a drill bit at the lower end thereof and to be coupled to a drill stem at the upper end thereof, said sub having a large upper flow channel extending to a small lower flow channel,

(b) an instrument housing secured in said upper flow channel with an annular zone between said housing and the inner walls of said upper flow channel for annular flow of drilling fluid past said housing,

(c) a flow crossover means having an isolation channel therein and located in the lower portion of said housing for directing the annular flow into said lower flow channel,

(d) a transmitter including a tape-wound magnetic core and a toroidal winding encased in a nonconductive body encircling said sub at a predetermined point spaced above said bit,

(e) a receiver including a tape-wound magnetic core and a toroidal winding encased in a nonconductive body encircling said sub immediately adjacent to said bit,

(f) oscillation means in said housing connected to said transmitter for generating alternating current in said sub and said bit, and

(g) means in said housing connected to said receiver through said crossover means for producing pressure pulses in said fluid above said housing at a rate dependent upon said resistivity.

5. An instrument sub for logging formation resistivity while drilling which comprises:

(a) an elongated sub adapted to receive a drill bit at the lower end thereof and to be coupled to a drill stem at the upper end thereof, said sub having a large upper flow channel extending to a small lower flow channel,

(b) an instrument housing secured in said upper flow channel with an annular zone between said housing and the inner walls of said upper flow channel for annular flow of drilling fluid past said housing,

(c) a flow crossover means having an isolation channel therein and located in the lower portion of said housing for directing the annular flow into said lower flow channel,

(d) a transmitter including a tape-wound magnetic core and a toroidal winding encased in a nonconductive body encircling said sub at a predetermined point spaced above said bit,

(e) a receiver including a tape-wound magnetic core and a toroidal winding encased in a nonconductive body encircling said sub immediately adjacent to said bit,

(f) means in said housing connected through said crossover means to said transmitter to energize said transmitter with alternating current,

(g) an electrically conductive spacer means between said transmitter and said receiver to permit lateral flow of current from said sub to said formation as well as to said bit, and

(h) means in said housing connected through said crossover means to said receiver and responsive to the voltage induced in said receiver by current flow to said bit producing pressure pulses in said fluid above said housing at a rate dependent upon said voltage.

6. A sub structure for logging formation resistivity while drilling which comprises:

(a) an elongated heavy-walled tube adapted to receive a bit at the lower end thereof,

(b) a transmitter having a tape-wound magnetic core with a toroidal winding mounted in the exterior wall of said tube in an insulating body,

(c) an outer abrasion protective metallic band covering said transmitter,

(d) an insulating band mounted on said tube below said transmitter,

(e) a conductive cylindrical spacer mounted on said tube below said insulating body,

(f) a receiver including a tape-wound magnetic core with a toroidal winding mounted on said tube in an insulating body below said spacer, and

(g) an outer abrasion protective metallic band covering said receiver whereby, upon excitation of said transmitter by alternating current, current flow is induced in said tube, part of which flows from said tube through said spacer to the adjacent formations to form a guard current and part of which flows through said tube in the region of said receiver and penetrates the formation at the bit-formation contact for inducing in said receiver a voltage representative of resistivity of the formation at said contact.

7. The combination set forth in claim 6, in which said transmitter has a winding of relatively few turns compared to the turns of the winding on the receiver.

8. In a borehole telemetering system wherein a formation dependent signal is produced which varies with a property of said formation as a drill bit penetrates said formation, the combination which comprises:

(a) valve means in the mud stream adjacent to said bit,

(b) actuating means responsive to said signal for repeatedly actuating said valve means at a time rate dependent upon said signal for producing variations in the impedance to mud flow,

(c) means for inhibiting the actuating means for a fixed time period at least as great as the recovery time or said valve means following each actuation thereof, and

(d) means at the mouth of the borehole responsive to pressure variations in said mud stream for recording a function representative of the rate of said pressure variations compensated for said fixed period.

9. In a borehole telemetering system wherein a formation dependent signal is produced which varies with a property of said formation as a drill bit penetrates said formation, the combination which comprises:

(a) valve means in the mud stream adjacent to said bit,

(b) a solenoid coupled to said valve means responsive to said signal normally to actuate said valve means repeatedly at a time rate proportional to said signal,

(c) means in circuit with said solenoid for inhibiting said solenoid for a fixed time period which is independent of said signal and at least as great as the recovery time of said valve means following each actuation thereof, and

(d) means at the mouth of the borehole responsive to pressure variations in said mud stream for recording a function representative of the rate of said pressure variations compensated for said fixed period.

10. A sub structure for logging formation resistivity while drilling which comprises:

(a) an elongated heavy-walled tube adapted to receive a bit at the lower end thereof,

(b) a transmitter having a magnetic core with a toroidal winding mounted in the exterior wall of said tube in an insulating body,

(c) an outer abrasion protective metallic band covering said transmitter,

(d) a conductive cylindrical spacer mounted on said tube below said band,

(e) an insulating band extending around said tube electrically to isolate said protective band from said spacer to avoid an electrical short circuit around said transmitter,

(f) a receiver located immediately adjacent to said lower end of said sub including a magnetic core with a toroidal winding mounted on said tube in an insulating body below said spacer, and

(g) an outer abrasion protective metallic band covering said receiver whereby, upon excitation of said transmitter by alternating current, current flow is induced in said tube, part of which flows from said tube through said spacer to the adjacent formations to form a guard current and part of which flows through said tube in the region of said receiver and penetrates the formation at the bit-formation contact for inducing in said receiver a voltage representative of resistivity of the formation at said contact.

11. A system for logging a well while drilling, where a drill collar has a bit at the end thereof, which comprises:

(a) a toroidal coil encompassing said drill collar at a point spaced above said bit,

(b) an electrical source means connected to said coil for applying alternating current thereto at a predetermined level to produce magnetic flux within said coil to induce electrical current flow through said drill collar to said bit,

(c) a detector coil encompassing said drill collar immediately adjacent to said bit for detecting current flow from said bit to formations of varying resistivity exposed and contacted by said bit,

(d) conversion means responsive to the voltage in said detector coil for producing a train of output pulses which are spaced one from another in dependence upon the magnitude of said voltage,

(e) signaling means for translating said output pulses into pressure pulses in the fluid in said well as to be detectable at the mouth of said well, and

(f) means for sensing and recording said conditions as a function of the depth of said bit in said well.

12. The combination set forth in claim **11** in which abrasion resistant shield means enshrouds both said toroidal coil and said detector coil.

13. The combination set forth in claim **11** in which an abrasion resistant shield ring enshrouds said toroidal coil but is mounted to prevent flow of current therethrough in any path that does not extend beyond the walls of said sub.

14. The combination set forth in claim **11** in which said conversion means produces said output pulses at variable time intervals which normally are shorter than the recovery time of said signaling means, and wherein means are provided for inhibiting actuation of said signaling means by said output pulses for a fixed period of time following each actuation thereof at least as great as the recovery time of said signaling means.

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