

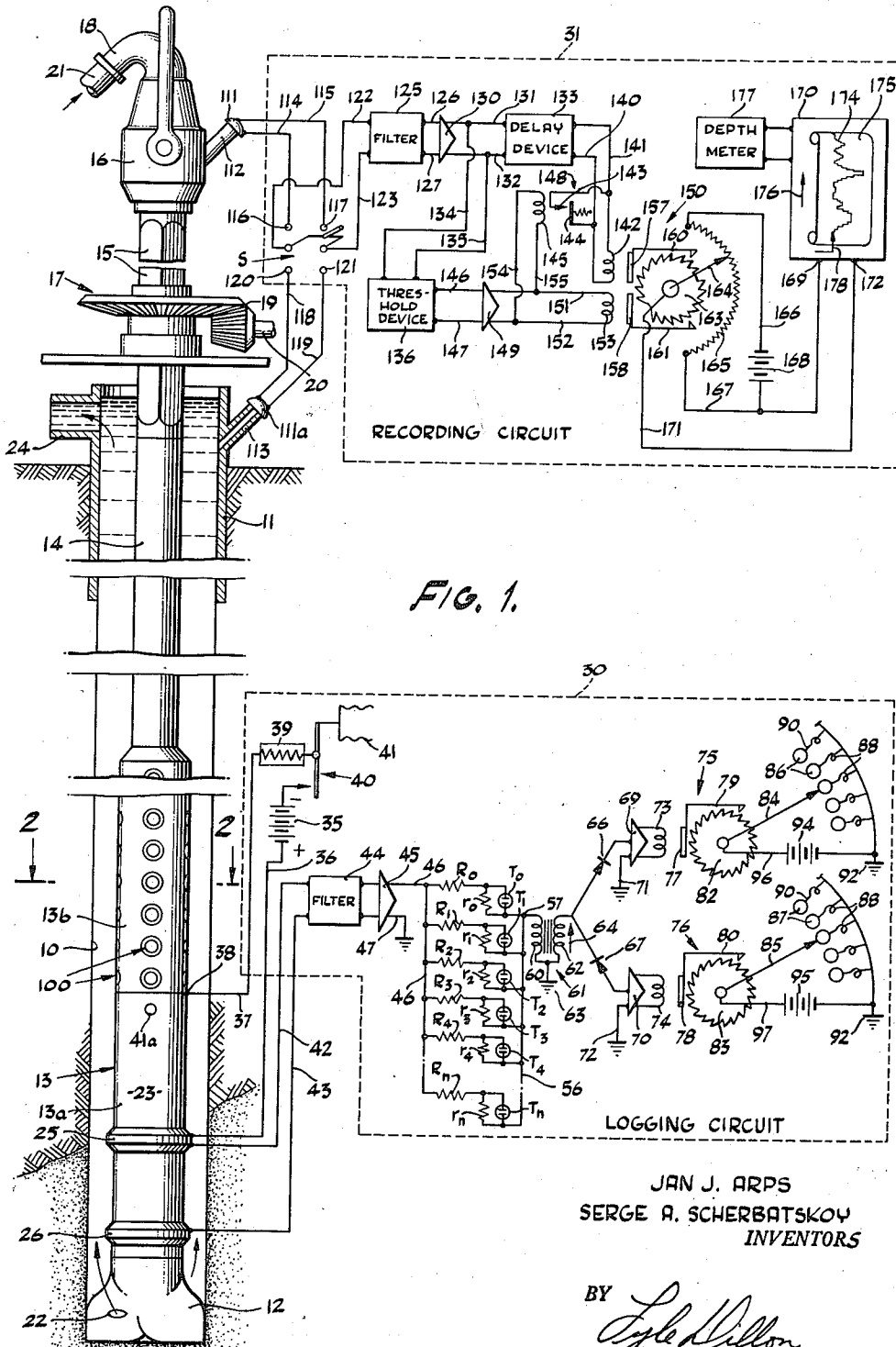
July 17, 1956

J. J. ARPS ET AL
LOGGING WHILE DRILLING

2,755,432

Filed June 27, 1952

4 Sheets-Sheet 1



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4 Sheets-Sheet 2

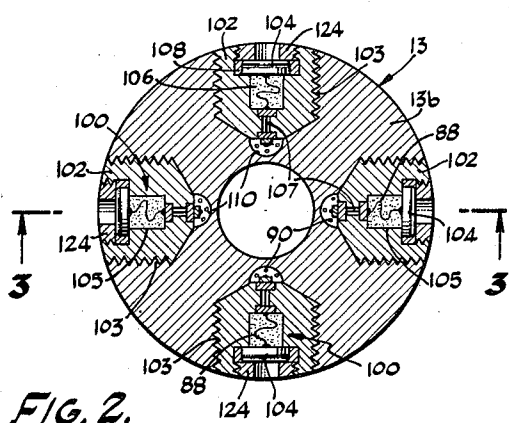


FIG. 2.

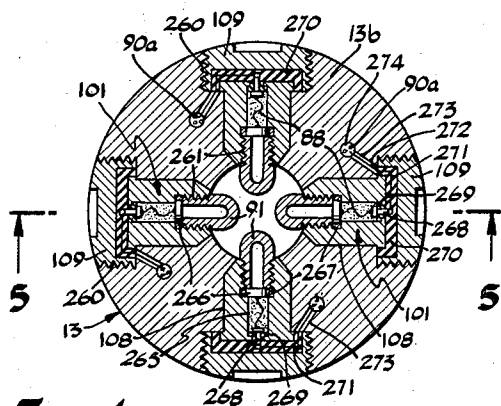


FIG. 4.

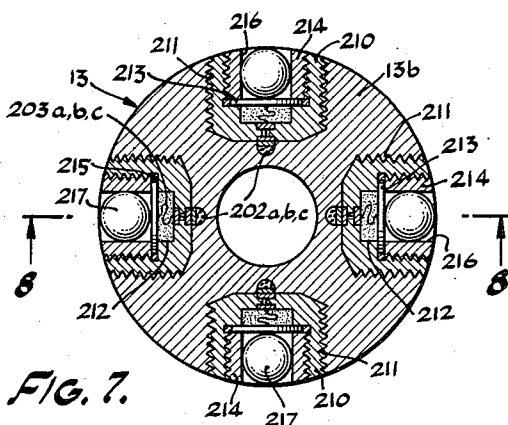


FIG. 7.

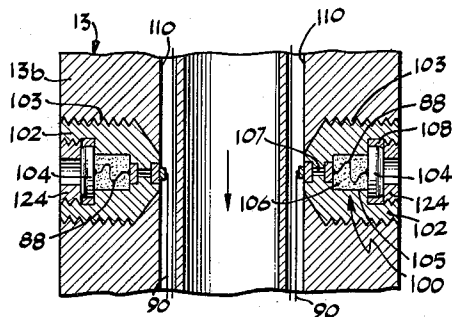


FIG. 3.

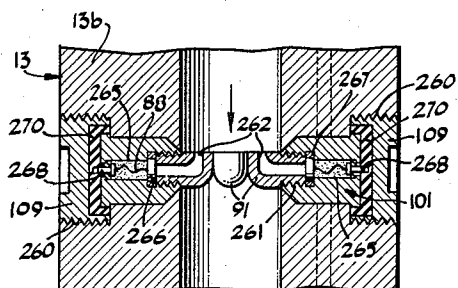


FIG. 5.

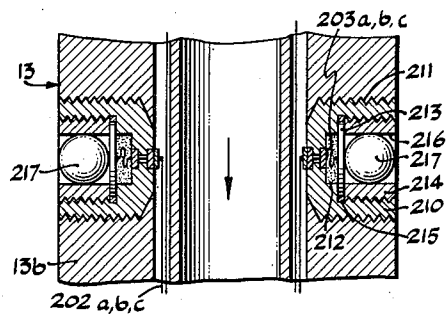


FIG. 8.

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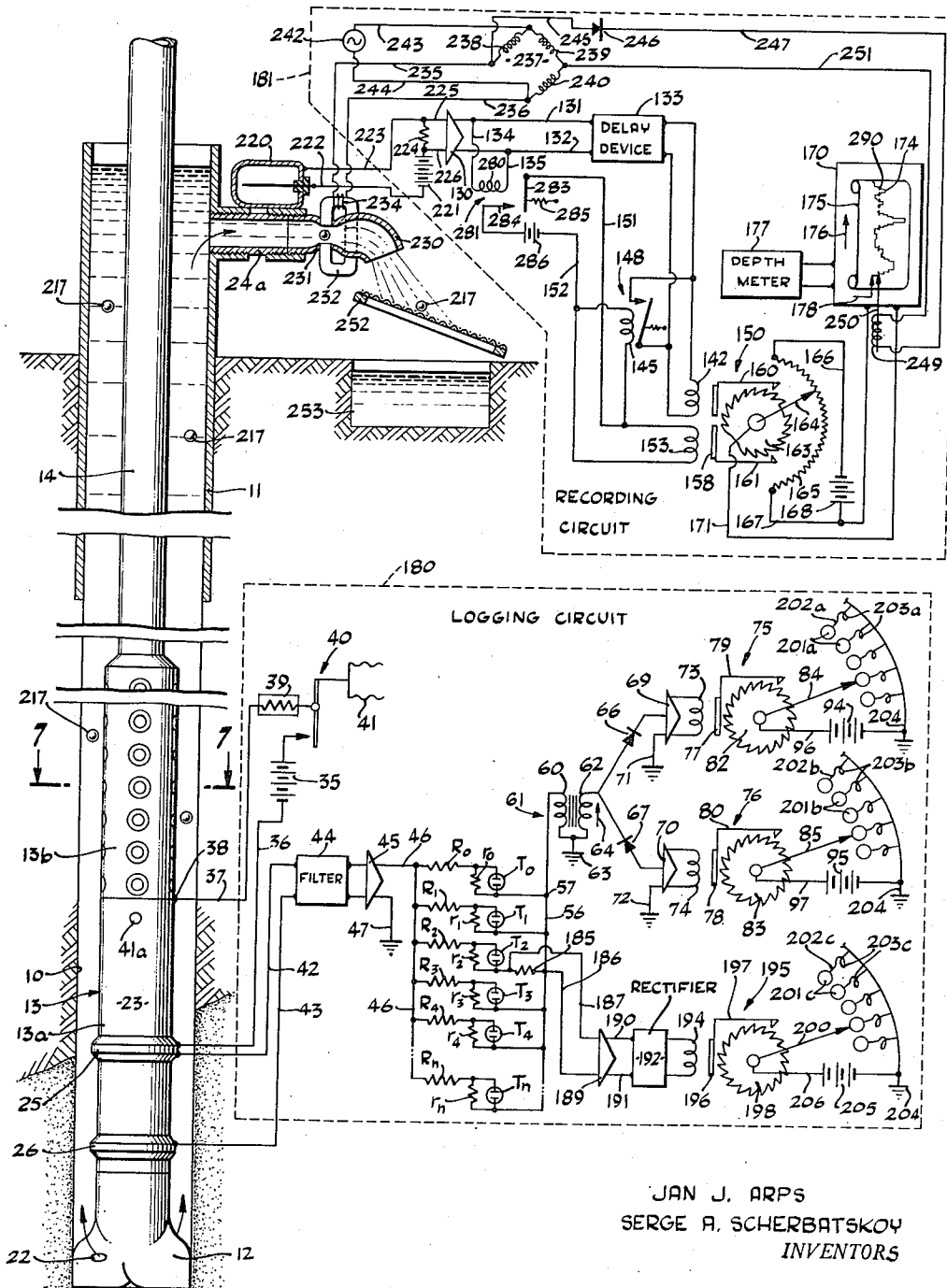
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LOGGING WHILE DRILLING

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4 Sheets-Sheet 3



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FIG. 9a.

VARIAION OF FORMATION RESISTIVITY
WITH BORE HOLE DEPTH.

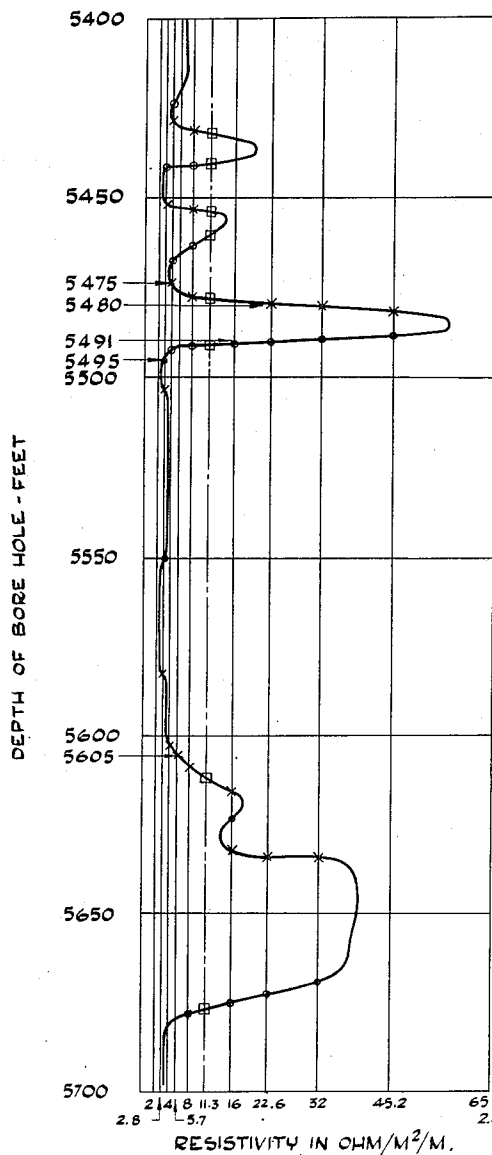
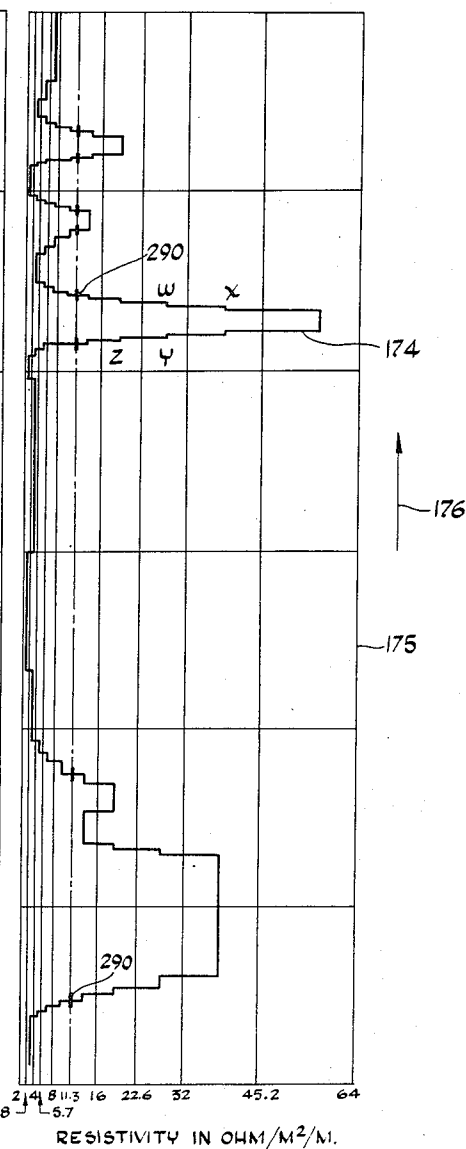


FIG. 9b.

RESISTIVITY LOG PRODUCED BY
SURFACE RECORDER.



- x LARGE CHARGE = INCREASE IN RESISTIVITY (TYPE A)
o WEAK CHARGE = DECREASE IN RESISTIVITY (TYPE B) BY
□ MAGNETIC (TYPE C)

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LOGGING WHILE DRILLING

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Application June 27, 1952, Serial No. 295,982

15 Claims. (Cl. 324-1)

This invention relates in general to exploration of geological strata traversed by earth boreholes, and more particularly to methods and apparatus for simultaneous drilling and logging of well boreholes.

Heretofore, in the conventional practice of well borehole logging, a suitable source of electric current has been located at the earth's surface outside of the borehole, and the current therefrom is applied through a suitably insulated conductor cable extending into the borehole to sensing apparatus therein to provide an electric current or signal in the conductor cable representative of the value of certain physical or electrical characteristics or quantities desired to be measured within the well borehole. The provision and maintenance of such insulated conductors in a drilling well, together with the drill pipe, in such a manner that drilling and electrical logging operations can be carried on simultaneously, have been found to be impracticable. Therefore, the usual well logging practice has been to interrupt the well drilling operation at suitable intervals to permit the removal of the drill pipe from the borehole, and the running into the borehole of the beforementioned conventional logging apparatus suspended from an insulated conductor cable while the drill pipe is absent from the borehole. The provision and maintenance of an insulated conductor cable for well borehole logging under any circumstances, whether or not present in the borehole together with the drill pipe, are different and costly.

The before-mentioned conventional intermittent logging practice has the disadvantage that the precise control at all times of the depth of drilling with respect to certain formations is difficult. Consequently, in many cases the desired shale body or the candidate productive formation may have been drilled through or passed by between the logging operation intervals, thereby possibly necessitating subsequent time-consuming and expensive corrective measures before the next intended step in the process of continued drilling or completion of the well can be undertaken.

Another disadvantage in the before-mentioned intermittent method of electrical logging, in which there is considerable delay between the drilling and logging operations, resides in the well known fact that the liquid from the drilling fluid continuously invades the penetrated formation surrounding the borehole, thereby changing the electrical characteristics of such formation for a substantial distance laterally from the borehole axis. Such invasion is progressive with time and, if permitted to continue for an appreciable length of time after drilling, before the logging measurements are taken, may result in sufficient contamination of the formations to cause possible confusion in the correct interpretation of some of the electrical characteristics of the formation thus measured.

The before-described difficulties are largely overcome by the present invention, which does not require an insulated conductor cable in the borehole at any time, but

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provides for the instant transfer of the results of the electrical logging operations or other similar measurements made within the borehole, to the earth's surface without employing the usual interconnecting insulating conductors, and this is accomplished while the drill pipe is within the well borehole and continuously during and simultaneously with drilling operations. The system of the present invention permits the electrical logging or other measuring apparatus to be contained within the lower end of the drill stem, preferably within the drill collar, and the process of making the actual logging measurements to be carried on there simultaneously with the drilling of the borehole, whereby the electrical logging measurements can be made of the freshly penetrated formation before excessive invasion of drilling fluid into the formation takes place.

Another advantage of the present invention resides in the simultaneous drilling and logging of the formation which it makes possible, by the continuous transmission of signals through the drilling fluid in the drill stem or in the annulus within the borehole surrounding the drill stem to receiving apparatus at the earth's surface, whereby a log representative of the formations being drilled through is continuously available.

Accordingly, an object of this invention is to provide a method and apparatus for logging earth boreholes or the measurements of electrical quantities within well boreholes, in which the necessity for using an insulated conductor extending into the borehole to the place of measurement is avoided.

Another object of this invention is to provide a logging system which permits the conducting of logging measurement operations and drilling operations simultaneously.

Another object of this invention is to provide a new method of and apparatus for the transmission of measurements of values of physical characteristics or quantities within the depths of a well borehole, to the earth's surface without the necessity of employing insulated conductor cables extending into the borehole.

The method and apparatus of the present invention are equally applicable to the exploration of boreholes simultaneously with the drilling operation and to the exploration of boreholes in which the drilling either has been completed or has been suspended.

The objects of this invention are attained in brief, by utilizing logging methods for detecting and measuring the variations in the earth characteristics or in measuring values of other physical quantities at a point in the borehole adjacent the drill bit while drilling is in progress, making a continuous measurement of such characteristics or values by suitable means located in the drill stem adjacent the drill bit, converting such measurements into pressure wave impulses or other suitable signals in the drilling fluid, by means of explosive means or other novel signalling devices located at or adjacent the lower end of the drill stem, whereby such signals travel upward through the drilling fluid in the drill stem or in the annular space surrounding the drill stem, to the earth's surface, and receiving and translating these impulses at the earth's surface into suitable electrical signals indicative of the measurements made within the well, for recording graphically on a chart in correlation with the depth of the corresponding drilling operations or point of measurement.

These and other objects, advantages, and features of novelty will be evident hereinafter in the following more detailed description of the invention.

In the drawings, which illustrate preferred embodiments and modes of operation of the invention, and in

which like reference characters designate the same or similar parts throughout the several views:

Figure 1 is a vertical sectional elevational view illustrative of a typical well borehole, showing the general arrangement of the apparatus of the invention, partially in elevation and partially diagrammatically;

Figure 2 is an enlarged cross-sectional view taken on line 2—2 of Figure 1;

Figure 3 is a fragmentary vertical sectional view taken on line 3—3 of Figure 2;

Figure 4 is an enlarged cross-sectional view of a modified form of a portion of the apparatus corresponding in location to that of Figure 2;

Figure 5 is a fragmentary vertical sectional view of the apparatus taken on line 5—5 of Figure 4;

Figure 6 is a vertical sectional view of a typical well borehole in which is illustrated, partly in elevation and partly in diagrammatic form, the general assembly of an alternative form of suitable apparatus for practicing the invention;

Figure 7 is an enlarged cross-sectional view of the apparatus taken on line 7—7 of Figure 6;

Figure 8 is a fragmentary vertical sectional view taken on line 8—8 of Figure 7;

Figure 9a shows a graphical representation of typical variations of formation resistivity along the length of a portion of a borehole; and

Figure 9b shows a graphical record or resistivity log produced by the indicating or recording portion of the apparatus of Figures 1 and 6, as obtained by logging measurements taken in correlation with the portion of the well illustrated by Figure 9a.

Referring first primarily to Figure 1, a longitudinal section of a typical well bore is shown, by way of example, having a lower uncased portion 10 and an upper portion in which a surface string of casing 11 has been set in accordance with conventional practice. Within the borehole is shown a rotary drilling string comprising a drill bit 12, a special drill collar 13, a conventional drill stem or drill pipe 14 connected at its upper end through a square kelly 15 to a swivel 16, which in turn may be supported by conventional well derrick apparatus (not shown), which usually includes a hook suspended from a suitable traveling block and drilling lines in a drilling well derrick. The square kelly 15 passes through conventional torsional gripping means in a rotary table 17, which is adapted to be rotated through the usual bevel gear and pinion drive, as shown at 19, which in turn is arranged to be driven, in accordance with usual practice, through shaft 20 by a suitable prime mover. Provision is made for circulating drilling fluid by introducing it under pressure from drilling fluid circulation pumps (not shown), through the flexible hose coupling 21, gooseneck connection 18, and thence through the swivel 16, kelly 15, and down through the drill pipe and passages in the drill collar, hereinafter more fully described, to be discharged through apertures 22 in the drill bit 12 into the bottom of the borehole. The drilling fluid thus introduced into the drill stem and discharged from the drill bit, circulates in return from the bottom of the borehole upward through the annular space between the borehole and the drill stem to the top of the borehole, from which it is finally discharged through a side outlet connection 24 leading from the surface casing 11 for return to a drilling fluid sump, from which it may be withdrawn and recirculated by the circulating pumps as just described.

The drill collar 13, which is attached to the lower end of the drill pipe 14 as before mentioned, comprises a lower, logging measurement and signal-generating instrument-containing portion 13a and an upper signal-transmitting portion 13b. The lower logging measurement portion 13a of the drill collar is provided with an outside electrical insulating coating, covering, or sleeve 23, which serves to electrically insulate that portion of the drill

collar from the surrounding drilling fluid and also serves to support a pair of longitudinally spaced-apart, annular electrode rings 25 and 26, which are thereby insulated from the drill collar and from one another. The before-mentioned insulating coating, covering, or sleeve 23 may be composed of suitable insulating material, such as rubber, neoprene, Bakelite, or other suitable insulating, abrasion-resistant materials. The drill bit 12 preferably is insulated electrically from the drill collar 13 by suitable means (not shown), such as a suitable threaded insulating bushing in the threaded joint between the lower end of the drill collar and the drill bit.

The logging measurement and signal-generating apparatus, which are contained within suitable fluid-tight enclosures within the lower portion 13a of the drill collar 13, are illustrated diagrammatically within the dotted rectangular enclosure 30.

The receiving and recording portion of the apparatus, located at the earth's surface outside of the well borehole, is illustrated within the dotted rectangular enclosure 31.

The signal generating and transmitting portion of the apparatus comprises essentially a suitable source of electric current, such as a battery 35 having its positive terminal connected by means of an insulated conductor 36 to one of the electrodes, such as the upper electrode 25, and having the negative terminal thereof connected by means of an insulated conductor 37 and a constant current element 39 to a suitable terminal 38 electrically connected at any suitable point to the metal body of the drill collar 13. An electric switch 40 is connected in series in the before-mentioned conductor 37, and is adapted to be operated by means of a suitable Sylphon bellows 41 suitably placed, as at 41a, in the drill collar 13 between the inner fluid flow passage and the outside of the drill collar. The switch 40 is thereby adapted to be operated by the flow or the differential fluid pressure set up between the inside and outside of the drill collar by the flow of the drilling fluid in the drill collar, and serves to keep the battery circuit open, to conserve the battery life, and to deactivate the signal-transmitting apparatus during the times the circulation of the drilling fluid is stopped for any reason, such as during the times when the drill string is being lowered into or withdrawn from the borehole, and when the mud circulating pumps are shut down for this or any other reason during interruption of drilling.

The ground terminal 38 in the drill collar is, as before mentioned, grounded to the metal of the drill string, and therefore, when the switch 40 is closed by the action of the flow of drilling fluid, the electrical circuit is completed, permitting an electric current to flow from the positive terminal of the battery 35 through the insulated conductor 36 to the annular electrode 25, and thence through the surrounding drilling fluid out into the adjacent earth formation, and return from the adjacent earth formation through the surrounding drilling fluid in the borehole to the metal portion of the drill collar, and through the insulated conductor 37, constant current element 39, and switch 40 to the negative terminal of the battery 35. The intensity or magnitude of the current thus flowing through this circuit from the battery 35 is substantially constant. As a result of the aforesaid current flow, a potential difference or voltage is established between the annular electrodes 25 and 26, the magnitude of which is representative of the before-mentioned resistivity of the adjacent formations surrounding the borehole.

The voltage thus picked up between the electrodes 25 and 26, which is representative of the resistivity of the adjacent formations surrounding the borehole, is applied to the input of the signal generating and transmitting apparatus, which translates this picked-up voltage into suitable signals which are transmitted to the earth's surface by means of properly and significantly

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timed explosions within the depths of the well bore-hole in a manner hereinafter more fully described.

As shown in Figure 1, the electrodes 25 and 26 are connected within the drill collar, through insulated conductor leads 42 and 43 and filter 44, to the input of a D.-C. amplifier 45. The filter 44 may be of substantially conventional design, adapted to pass only very low frequencies and to exclude a substantial amount of noise having frequencies above the frequencies of the logging measurement variations. For example, the filter 44 may be a resistance capacitance network having a time constant of several seconds or more per cycle to obviate the undesired actuation of the neon tube network at frequent intervals when the potential picked up by the electrodes 25 and 26 hovers close to a critical value. The D.-C. output of the amplifier 45 is applied through conductors 46 and 47 across a plurality of neon tubes, a representative portion of which is illustrated at T_0 - T_n , connected in series-parallel through suitable resistors, as hereinafter more fully described. The conductor 46 leading from the D.-C. amplifier 45 is connected to one side of each of the neon tubes T_0 - T_n through series resistors R_0 - R_n , respectively. The other sides of the neon tubes T_0 - T_n are connected to a common conductor lead 56, which is in turn connected at 57 with one end of the primary winding 60 of a transformer 61. The opposite end of the primary winding 60 is grounded at 63 for completion of the circuit through the ground connection to the grounded conductor 47 leading from the output of the D.-C. amplifier 45. The neon tubes T_0 - T_n are shunted by suitable resistors r_0 - r_n , respectively.

The secondary winding 62 of the transformer 61 is connected through oppositely polarized rectifiers 66 and 67 to one terminal of each of amplifiers 69 and 70, respectively. The other input terminals of amplifiers 69 and 70 are grounded at 71 and 72, respectively, for the ground return circuit to connection 63 of the transformer 61. The output connections of the amplifiers 69 and 70 are connected to the respective windings of electromagnets 73 and 74 of ratchet-type sequence switches illustrated at 75 and 76.

Each of the ratchet-type switches includes an armature, as shown at 77 and 78, located adjacent to and adapted to be actuated by the respective electromagnets 73 and 74. The armatures 77 and 78 have attached thereto suitable pawls 79 and 80, each adapted to make one-way ratcheting engagement with the ratchet teeth of ratchet wheels 82 and 83, respectively, in such manner that when the armatures 77 and 78 are actuated by electromagnets 73 and 74, the ratchet wheels 82 and 83 are rotated step-wise in counterclockwise direction.

Each of the ratchet wheels 82 and 83 of switches 75 and 76 carries fixed thereto a switch arm, as shown at 84 and 85, for rotation therewith step-wise into contact with a plurality of electrical contact points, as shown respectively at 86 and 87. Each of the contact points of the ratchet switches is connected through a conductor, such as shown at 90, to an ignition filament 88, and thence to ground 92, with completion of the electrical circuit through the ground connection to batteries 94 and 95, which are in turn connected through conductors 96 and 97, respectively, to the ratchet switch arms 84 and 85. Each of the ignition filaments 88 is located in an explosive signal unit contained within the upper signal-transmitting portion 13b of the drill collar 13, as will be hereinafter more fully described.

As before mentioned, each of the contact points 86 and 87 of the ratchet switches 75 and 76 is connected by a separate insulated conductor lead, as shown at 90 in Figures 1, 2, and 3, or as shown at 90a in Figures 4 and 5, to a separate one of the plurality of ignition filaments of the powder chambers or cartridges contained in the signal units of the type shown at 100 in Figures 2 and 2 or of the type shown at 101 in Figures 4 and

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5. Each of the explosive signal units of the type illustrated in Figures 2 and 3 comprises a replaceable, externally threaded body or plug 102 fitted into suitable, internally threaded, laterally outwardly facing sockets, as shown at 103, in the outside surface of the upper signal-transmitting portion 13b of the drill collar 13. Each of the signal unit bodies 102 is formed with a coaxial inner chamber 105 for containing a suitable cartridge or quantity of powder. The before-mentioned ignition filament 88 extends through the chamber or cartridge from a suitable gas- and fluid-tight conductor inlet connection 107 at the rear end of the chamber, to a frangible diaphragm 104 at the forward end of the chamber. Each of the ignition filaments 88 is thus grounded to the drill collar body (as schematically illustrated at 92 in Figure 1) at its outer end through the frangible metal diaphragm 104. The diaphragm 104 serves as a fluid-tight closure for the outer end of chamber 105, and each metal diaphragm 104 is held in place by means of a threaded annular nut 124 and an intermediate annular gasket 108.

The several conductors 90, which make electrical interconnection between the switch contact points 86 and 87 and the several corresponding ignition filaments 88 contained in the signal units, extend through suitably positioned, longitudinal ducts in the drill collar body, as shown at 110 in Figures 2 and 3, and which interconnect the upper signalling portion 13b and lower instrument-containing portion 13a of the drill collar. The conductor inlet connection 107 extends rearwardly from the rear end of the signal unit body into the ducts 110, where electrical connection is made with the conductors 90. For the purpose of simplification, only three of the conductors 90 are shown in each of the ducts 110, although the actual number of such conductors would be considerably greater and equal to the number of explosive signal units contained in the upper portion 13b of the drill collar, and also equal to the total number of switch contact points 86 and 87 of switches 75 and 76.

In general, the construction of the explosive signal units and electrical wiring and switching system employed in connection therewith in the drill collar may be similar to that employed in convention gun perforating equipment.

The surface apparatus for receiving and recording the signals transmitted from the hereinbefore-described subsurface signal-transmitting apparatus contained within the dotted enclosure 30 within the drill collar 13, is, as hereinbefore mentioned, shown diagrammatically within the dotted rectangular enclosure 31. This receiving apparatus includes microphones 111 and 111a. Microphone 111 is connected through a short length of pipe 112, which makes connection through the side of the swivel 16, at a suitable point, to the fluid flow channel therein extending between the swivel gooseneck 18 and the flow passage within the Kelly bar 15.

The microphone 111a is connected through a short length of pipe 113 to a side opening in the surface casing 11 at a point below the fluid level therein and preferably, although not necessarily, at a sufficient distance under the surface of the earth to be relatively free of engine and exhaust noises. The output of the microphone 111 is connected through conductors 114 and 115 to one pair of terminals 116 and 117, respectively, of a double-pole double-throw switch S. The output of microphone 111a is similarly connected through conductors 118 and 119 to the opposite pair of terminals 120 and 121, respectively, of the aforesaid double-pole double-throw switch S. Conductors 122 and 123 lead from the knives of the double-pole double-throw switch S to the input of a filter 125, and thence through conductors 126 and 127 to the input of an amplifier 130. The output from the amplifier 130 is connected to two parallel, branch circuits, one 75 branch circuit extending through conductors 131 and

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132 to the input of a delay device 133, and the other branch circuit extending through conductors 134 and 135 to a threshold device 136.

The output from the delay device 133 is connected through conductors 140 and 141 to the windings of an electromagnet 142 forming a portion of the actuating means of a reversible ratchet-type switch shown at 150. Across the conductors 140 and 141 leading from the delay device is connected a shorting switch 148 having a contact point 143 and an armature 144. The armature 144 is adapted to make electrical connection with the point 143 when actuated by means of an electromagnet 145.

The output connections 146 and 147 from the threshold device 136 lead to the input of an amplifier 149, the output of which is connected through conductors 151 and 152 to the windings of another electromagnet 153 forming another portion of the actuating means of the before-mentioned ratchet switch 150. The windings 145 of the before-mentioned electromagnet 145 of the shorting switch are connected through conductors 154 and 155 across the amplifier output conductors 151 and 152.

The before-mentioned ratchet switch 150 includes a pair of separate armatures 157 and 158, each adjacent to and adapted to be actuated by the electromagnets 142 and 153, respectively. The armatures 157 and 158 have attached thereto suitable pawls 160 and 161, each adapted to make one-way ratcheting engagement with the ratchet teeth carried on opposite halves of a toothed ratchet wheel 163. As shown in the drawings, the opposite halves of the ratchet wheel 163 carry oppositely facing sets of ratchet teeth, the pawl 160 being adapted to make one-way ratcheting engagement with one set of the ratchet teeth on one side of the wheel, and the pawl 161 being adapted to make one-way ratcheting engagement with the other set of ratchet teeth on the opposite side of the wheel. Thus, when the armature 157 is actuated by the electromagnet 142, the ratchet wheel 163 is rotated step-wise in a counterclockwise direction, and when the armature 158 is actuated by the electromagnet 153, the ratchet wheel 163 is rotated step-wise in a clockwise direction.

The shaft of the ratchet wheel 163 carries fixed thereto a radial contact arm 164 which is adapted upon rotation of the ratchet wheel 163 to make sliding electrical contact with an arcuate potentiometer resistor element 165, which is placed concentric with the shaft of the ratchet switch. Opposite ends of the resistor element 165 are connected through conductors 166 and 167 to opposite terminals of a battery 168, and the conductor 167 is also connected to one input terminal 169 of a suitable meter or recorder 170. The switch contact arm 164 is electrically connected through conductor 171 to the other input connection 172 of the meter or recorder device 170. The recorder 170 is provided with a strip chart 175 adapted to be driven by means of a suitable depth meter 177 such that the motion of the strip chart 175 relative to the pen 178 is maintained in predetermined correlation with the depth of the electrodes 25 and 26 within the borehole 10. Suitable apparatus which may be adapted to perform the service of the depth meter 177 is shown in Figures 2, 3, and 4 of the copending Arps application, Serial No. 90,503, filed April 29, 1949, now abandoned.

Referring now primarily to Figure 6, in which an alternative form of the apparatus of the invention is illustrated, a longitudinal section of a typical well borehole is shown, by way of example, similar to that hereinbefore described in connection with Figure 1, having a lower uncased portion 10 and an upper portion in which a surface string of casing 11 has been set in accordance with conventional practice. Within the borehole is shown a rotary drill string of substantially the same general construction and arrangement as that hereinbefore described in connection with Figure 1, and therefore the elements thereof which are common to both figures are designated by the same or similar reference characters.

The signal generating and transmitting portion of the

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apparatus contained within the drill collar, and illustrated within the dotted rectangular enclosure 180 of Figure 6, may be identical to that hereinbefore described in connection with Figure 1 as contained within the dotted rectangular enclosure 30, except for the following apparatus:

Between the conductor 56 and a suitable one of the neon tubes, for example T₂, is connected a resistor 185, and across this resistor is connected a pair of conductors 186 and 187 which lead to the input of an amplifier 189. The output of the amplifier 189 is connected through conductors 190 and 191 to the input of a suitable rectifier 192. The output from the rectifier 192 is connected to the windings of an electromagnet 194 for actuation of a ratchet switch 195. The construction of ratchet switch 195 is similar to that of ratchet switches 75 and 76 hereinbefore described in connection with Figure 1, and includes an armature as shown at 196 located adjacent to and adapted to be actuated by the electromagnet 194. The armature 196 carries attached thereto a pawl 197, which is positioned to make one-way ratcheting engagement with the ratchet teeth of ratchet wheel 198 in such manner that when the armature 196 is actuated by the electromagnet 194, the ratchet wheel 198 is rotated step-wise in counterclockwise direction. The ratchet wheel 198 carries a switch arm 200 for rotation step-wise therewith into contact with a plurality of electrical contact points 201c.

Each of the contact points 201c of the ratchet switch 195 is connected through conductors, such as shown at 202c, to ignition filaments as shown at 203c, and thence to ground at 204, through which the return electrical circuit is completed to one terminal of battery 205. The other terminal of battery 205 is connected through conductor 206 to the switch arm 200 of the ratchet switch 195.

The ratchet-type switches 75 and 76 shown in Figure 6 are substantially the same as those shown at 75 and 76 in Figure 1, except that the switch arms 84 and 85 in the apparatus of Figure 6 are arranged to make electrical contact with switch contact points 201a and 201b, respectively. These switch contact points 201a and 201b are connected through conductors 202a and 202b, respectively, to ignition filaments as shown at 203b. As in the other switches, the ignition filaments 203b are grounded at 204 to the metal body of the drill collar, and the electrical connection is completed through such ground connection to the batteries 94 and 95 and thence through conductors 96 and 97, respectively, to the arms 84 and 85 of ratchet switches 75 and 76, respectively.

The ignition filaments 203a, 203b, and 203c are contained within Type A, B, and C signal units, respectively. The Type A, Type B, and Type C signal units controlled by the ratchet-type switches 75, 76, and 195 are of different construction and have different characteristics, as more fully outlined hereinafter.

Each of the ignition filaments represented at 203a, 203b, and 203c is located in a different explosive signal device or cartridge contained within the upper signalling portion 13b of the drill collar 13 in a manner similar to that hereinbefore described in connection with switches 84 and 85 of Figure 1. However, the explosive signalling devices of Type A, Type B, and Type C, containing the ignition filaments 203a, 203b, and 203c, are preferably of the type illustrated in Figures 7 and 8, and comprise a replaceable plug 210 threaded into suitable, radially outwardly facing sockets, as shown at 211, formed in the outside surface of the signal-containing portion 13b of the drill collar 13.

Within the rearward portion of each plug 210 is formed a cylindrical chamber, as shown at 212, adapted to contain a cartridge or a suitable charge of powder or the like explosive material. The ignition filament 203a, 203b, or 203c is grounded at one end to a frangible metal diaphragm 213, which serves as a fluid-tight closure for the outer end of the chamber 212 and serves also as a ground connection to the drill collar body corresponding to that diagrammatically illustrated at 204 in Figure 6. Each metal diaphragm 213 is held in place against an outward-

ly facing shoulder at the forward end of the chamber 212 by means of an annular nut 214, and a fluid-tight seal is effected between the diaphragm and the bore of the plug by an annular gasket 215. Spherical signal elements or pellets, as shown at 217, are contained within the bores 216 of the elongated annular nuts 214, and may be releasably retained therein by any suitable means, such as by a suitable cementitious material placed in the spaces between the spheres and the inside surfaces of the bores 216, which will permit them to be expelled into the fluid surrounding the drill collar upon ignition of the relatively small explosive charge in chamber 212 by means of ignition filaments 203a, 203b, and 203c.

Three different types of spherical signal elements or pellets 217 are provided in connection with the apparatus of Figure 6. Those signal pellets contained in the explosive signal units the ignition filaments 203a of which are connected with the contact points of ratchet switch 75, contain a relatively small amount of radioactive material, and for convenience are herein referred to as Type A signal pellets, which produce Type A signals. The pellets contained in the explosive signal units the ignition filaments of which are connected to the contact points of ratchet switch 76, contain a relatively large amount of radioactive material, and are referred to herein as Type B signal pellets, which produce Type B signals. The signal pellets contained in the explosive signal units the ignition filaments 203c of which are connected to the contact points of ratchet switch 195, contain a quantity of ferro-magnetic material such as iron, and are similarly referred to herein as Type C signal pellets, which produce Type C signals.

All of the signal pellets are preferably made of a resilient material, such as rubber, neoprene, or the like material, which will resist being crushed, broken, or destroyed between the rotating drill pipe and the inside surface of the borehole wall. These pellets are also preferably slightly buoyant with respect to the drilling fluid, to prevent them from sinking through the drilling fluid when circulation is interrupted and to facilitate their circulation with the drilling fluid from their point of release from the drill collar within the borehole to the point of reception in the receiving apparatus at the earth's surface.

The signal receiving and recording portion of the apparatus of Figure 6 is illustrated diagrammatically within the dotted enclosure 181, and comprises the same apparatus as that disclosed with the dotted enclosure 31 in Figure 1, except as follows: Instead of employing microphones such as those illustrated at 111 and 111a in Figure 1 adapted to be electrically connected through switch S and through filter 125 to the D.-C. amplifier 130, a radioactivity radiation detector device, preferably one such as an ionization chamber, although other well known types of radiation detector devices may be used, is positioned as shown at 220, adjacent the circulating fluid outlet pipe 24a. The ionization chamber 220 is connected to a suitable source of high potential D.-C., such as battery 221, through conductors 222 and 223 and resistor 224. The opposite ends of the resistor 224 are connected through conductors 225 and 226 to the input of D.-C. amplifier 130.

The output of amplifier 130 is connected to two parallel branch circuits, one branch circuit extending through conductors 131 and 132 to the delay device 133, and the other branch circuit extending through conductors 134 and 135 to the windings of an electromagnet 280 of a threshold device 281. The threshold device 281 includes an armature 283 biased to an open position relative to an electrical contact point 284 by means of a spring 285 but movable upon energization of the electromagnet 280 into electrical contact with point 284. The armature 283 and the contact point 284 are connected through battery 286 and conductors 151 and 152 to the electromagnets 145 and 153 of the shorting switch 148 and ratchet switch 150, respectively, in the manner hereinbefore described

in connection with Figure 1. The delay device 133 is also connected to the switch 148 and the electromagnet 142 of the ratchet switch 150 in the manner hereinbefore described in connection with Figure 1.

The outer end portion of the circulating fluid outlet pipe 24a is provided with an extension, as shown at 230, having an intermediate section or passage of reduced diameter, as shown at 231. This extension 230 is preferably made of a non-magnetic material, such as aluminum, brass, or a suitable plastic material. The opposite, adjacent ends of a C-shaped core 232 are positioned at opposite sides of the before-mentioned passage 231, whereby magnetic flux in the core 232 may be caused to pass through the area forming said passage. The core 232 is provided with a suitable winding 234, which is connected through conductors 235 and 236 into one leg of an alternating current Wheatstone bridge circuit 237. The other legs of the Wheatstone bridge comprise reactances 238, 239, and 240. Alternating current supply for the Wheatstone bridge 237 is provided by means of a suitable alternating current generator 242 which is connected to one diagonal of the Wheatstone bridge through conductors 243 and 244. The opposite diagonal of the Wheatstone bridge 237 is connected through conductor 245 to a rectifier 246 and thence through conductor 247, the actuating windings of an electromagnet 249 of a marker pen 250, and return through conductor 251. The marker pen 250 is adapted, when the electromagnet 249 is energized, to make a reference mark on the chart 175.

The fluid discharged through the fluid outlet pipe 24a and pipe extension 230 is passed through the shale shaker or other suitable screening or separating device 252 to the mud sump 253, to be subsequently withdrawn by the fluid circulating pumps and recycled through the drill stem in the manner hereinbefore described. The signal pellets are separated out by the shale shaker or screening device 252, and collected by suitable means for reuse in the system.

The operation of the apparatus of Figure 1 is as follows: During circulation of the drilling fluid, a differential pressure is applied across the Sylphon bellows device 41 resulting in the maintenance of switch 40 closed. Current is thereby permitted to flow from the battery 35 through conductor 36 to electrode 25 and out through the surrounding drilling fluid and adjacent formations and return to exposed, uninsulated portion of the drill collar, and thence through conductor 37, constant current element 39, and switch 40 to the battery 35. The current thus applied to the formations surrounding the borehole will be of substantially constant value, and a potential field will thereby be set up in the surrounding formations, in the manner well known in the electrical logging art, which is a function of the resistivity of such surrounding formations. A portion of this potential field or voltage, representative of the resistivity of the formation adjacent electrodes 25 and 26, is picked up by these electrodes and is applied through conductors 42 and 43 and filter 44 to the input of amplifier 45. Any other suitable arrangement of electrodes, well known in the electrical logging art, may be employed, from which a potential difference can be obtained, for application to the input to amplifier 45, and which is representative of the resistance, resistivity, or other desired electrical characteristic of a portion of the adjacent formations. Likewise, a potential difference representative of any other physical quantity desired to be measured within the borehole may be applied to the input of amplifier 45. The resultant output of amplifier 45 is applied across the neon tubes T_0 - T_n by way of conductor 46 through the parallel-connected group of resistors R_0 - R_n and r_0 - r_n to conductor 56, and thence through the primary 60 of the transformer 61 and return through ground to conductor 47.

The values of the resistors R_0 - R_n and r_0 - r_n are such that for any given potential output from amplifier 45 different potential drops occur across each of the neon

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tubes T_0 - T_n such that the breakdown voltage or ignition potential of each of the neon tubes is different, and such, for example, that tube T_0 will have the lowest effective breakdown potential, and the tubes T_1 , T_2 , T_3 , T_4 , and so on to T_n will have progressively higher predetermined breakdown voltages. Thus, as the output voltage of amplifier 45 is, for example, increased, tube T_0 will ignite first, then tubes T_1 to T_n successively thereafter as the amplifier voltage rises. It is to be understood that the resistance network and the neon tubes illustrated are only a portion of those which would be actually employed, the number of such neon tubes and the voltage breakdown or ignition differences across such tubes being made such as to accommodate the full range of potential differences appearing at the output of amplifier 45 corresponding to the full range of resistivities encountered at the pick-up electrodes 25 and 26.

The resistors are also preferably of such values as to place the ignition and extinguishing potentials of each of the neon tubes T_0 - T_n as close together as possible.

For convenience of illustration of the operation of the apparatus, it may be first assumed that during a given time interval while the drilling progresses, the resistivity of the formation adjacent the electrodes 25 and 26 remains substantially constant. Consequently, the voltage picked up by electrodes 25 and 26 and the output voltage of the amplifier 45 also remains correspondingly at a substantially constant value. Let it be further assumed that this substantially constant value is sufficient to exceed the ignition voltages of the neon tubes T_0 and T_1 as applied through the resistance network shown, but is insufficient to ignite the rest of the neon tubes in the circuit. Under this initially assumed condition, the circuit channels comprising the neon tubes T_0 and T_1 are conductive, while the remaining circuits comprising the tubes T_2 - T_n are non-conductive. Under this condition, a current flows from one of the output terminals of the amplifier 45 through the two conductive channels comprising tubes T_0 and T_1 in parallel, and thence through the primary 60 of transformer 61, and return to the other terminal connection of the amplifier 45. This current being substantially constant, substantially no current is induced in the secondary winding 62 of the transformer 61. Therefore, as long as the resistivity of the adjoining formation does not change, the current flowing through the winding 60 of the transformer 61 is constant, and hence no output voltage is induced across the secondary winding 62 of the transformer.

For purposes of further illustration, two separate formation resistivity change conditions, designated for convenience as condition change (a) and condition change (b), may be considered.

In condition change (a), it may be assumed that the electrodes 25 and 26 are moved into a position opposite formations having greater resistivity than that hereinbefore mentioned, and consequently the voltage across the electrodes 25 and 26 and output terminals of the amplifier 45 is correspondingly increased. When such voltage increase reaches a value sufficient to cause neon tube T_2 to ignite, the resultant current flowing from the output terminals of the amplifier and through the primary winding 60 of the transformer 61 is suddenly increased in value by the amount of current flowing through tube T_2 . This sudden current increase induces a momentary, unidirectional voltage surge in the secondary winding 62 of the transformer 61 (which in this case may be considered a positive surge), such voltage surge having, for example, a direction or polarity as designated by the arrow 64.

In condition change (b), it may be assumed that the electrodes 25 and 26 are moved into a position opposite formations having lower resistivity than that first mentioned, and consequently the voltage across the output terminals of the amplifier 45 is correspondingly decreased. When this voltage output is thus decreased to a value insufficient to maintain the tube T_1 conductive, and con-

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sequently tube T_1 extinguishes itself, a sudden decrease in current through the primary winding 60 of transformer 61 takes place. This sudden current decrease in current flowing through the winding 60 of the transformer 61 induces a momentary, unidirectional voltage surge in the secondary winding 62 of the transformer 61 (which in this case may be considered a negative voltage surge), such voltage surge having a direction or polarity in the direction opposite to that indicated by the arrow 64.

Thus, when there is no change in the resistivity of the formation position adjacent the electrodes 25 and 26, no voltage is induced across the secondary winding 62 of the transformer 61. When the resistivity increases to a given predetermined value, a positive, unidirectional voltage surge in the direction of the arrow 64 appears across the winding 62. When the resistivity decreases to a predetermined value, a negative, unidirectional voltage surge in the direction opposite to the arrow 64 appears across the winding 62 of the transformer 61.

As the resistivity of the formations adjacent the electrodes 25 and 26 continues to increase in value, the tubes T_0 - T_n successively ignite as such resistivity in its reduction successively passes corresponding predetermined separate values. Inversely thereto, the tubes T_n - T_0 are successively extinguished as the resistivity adjacent the electrodes 25 and 26, in decreasing, successively passes predetermined separate increased values.

Consequently, whenever the resistivity of the formations adjacent the electrodes 25 and 26, while increasing, passes one of a number of different predetermined values, a corresponding additional one of the neon tubes is ignited, thereby inducing a positive, unidirectional pulse in the secondary 62 of the transformer 61, which is free to pass through the rectifier 66, but cannot pass through rectifier 67 which is in a position of opposite polarity in the circuit. The resulting positive, unidirectional pulse conducted through rectifier 66 and applied to the amplifier 69 causes a current pulse to flow through the winding of the electromagnet 73 of the ratchet switch 75. The resultant movement of armature 77 and pawl 79 turns the ratchet wheel 82 through a counterclockwise angle just sufficiently to move the contact arm 84 from one of the switch contact points 86 to the next adjacent switch contact point. Each such movement of the switch arm 84 to a successively adjacent contact point 86 closes the electrical circuit through battery 94 through a new ignition filament, such as shown at 88, resulting in the ignition of one of the large explosive signal charges contained in the signal-transmitting portion 13b of the drill collar.

Similarly, whenever the resistivity of the formations adjacent the electrodes 25 and 26, while decreasing, passes one of a number of predetermined values, a corresponding additional one of the neon tubes is extinguished, thereby inducing a negative pulse in the secondary 62 of the transformer 61, which is free to pass through rectifier 67 but cannot pass through rectifier 66 which is in a position of opposite polarity in the circuit. The resulting unidirectional pulse conducted through rectifier 67 and applied to the amplifier 70 causes a current pulse to flow through the winding of the electromagnet 74 of the ratchet switch 76. The resultant movement of armature 78 and pawl 80 turns the ratchet wheel 83 through a counterclockwise angle just sufficient to move the contact arm 85 from one of the switch contact points 87 to the next adjacent switch contact point. Each such movement of the switch arm 85 to a successively adjacent contact point 87 closes the electrical circuit through battery 95 through an ignition filament, such as that shown at 88, resulting in the ignition of one of the small explosive signal charges contained in the signal-transmitting portion 13b of the drill collar.

From the foregoing, it is apparent that, whenever the drill bit, as it progresses downward during drilling, or is otherwise moved through the borehole, moves the electrodes 25 and 26 into position in the drilled borehole

opposite formations of increased resistivity, and when such increased resistivity reaches any one of a number of different, predetermined values, one of the large explosive signal units is fired, thereby producing a relatively large or strong signal impulse which travels upward through the drilling fluid in the borehole, and whenever the drill bit, as it progresses downward, or is otherwise moved as aforesaid, moves the electrodes 25 and 26 in the drilled borehole to a position opposite formations of decreased resistivity, and when such decreased resistivity reaches any one of a number of different, predetermined decreased values, a small or relatively weak one of the explosive signal units is fired, thereby producing a relatively weak signal impulse which travels upward through the drilling fluid in the borehole. No signal units are fired if the resistivity of the formations encountered by the advancing drill bit does not vary, and also no signal units are fired when such resistivity varies unless the variation is sufficient to reach one of the hereinbefore-mentioned predetermined values.

Thus, a signalling system has been provided capable of immediately apprising the observer or receiver at the earth's surface of any predetermined amount of increase or decrease in the resistivity of the formations being drilled. By correlating these signals thus received with the depth of the formation drilled, the observer is capable of plotting a graph showing the variation of resistivity with respect to depth of the borehole. Such a graph plotted by suitable receiving apparatus at the earth's surface, as hereinafter more fully described, is illustrated in Figure 9b.

The relatively strong and relatively weak pressure pulsations created by the firing of the large and small signal units corresponding to condition changes (a) and (b), respectively, as hereinbefore described, pass upward through the fluid in the borehole, where they are detected or picked up at the earth's surface by means of the microphones 111 and 111a. The resulting electrical impulse produced by either the microphone 111 or 111a is impressed through the pairs of conductors 114, 115 or pairs of conductors 118, 119, respectively, depending upon which microphone is selected by the switch S, and thence through conductors 122 and 123, filter 125, and through conductors 126 and 127 to the input of amplifier 130. When the fluid pressure impulse reaching the top of the well borehole and picked up by either one of the microphones is a relatively weak one, from a small explosive signal unit charge, the output pulse from amplifier 130 is of correspondingly low magnitude. When the fluid pressure pulse reaching the microphone 111 or 111a is a relatively great one resulting from a large one of the signal unit charges, the resulting output pulse from amplifier 130 is of correspondingly greater magnitude. Thus two types of electrical impulses are produced out of the amplifier 130: electrical impulses of relatively high magnitude caused by the firing of the large explosive signal units, under condition change (a), and electrical impulses of relatively low magnitude produced by the firing of the small explosive signal units, under condition change (b).

Upon occurrence of a low magnitude electrical impulse from the amplifier 130, such impulse is conducted through conductors 131 and 132 to the delay device 133 and also through the branch circuit conductors 134 and 135 to the threshold device 136. Such low magnitude impulse is insufficient to actuate the threshold device 136, and thus such impulse does not pass beyond the threshold device. The electrical impulse delivered to the delay device 133, however, continues on, after a momentary time delay, through conductors 140 and 141 to the windings of the electromagnet 142 of the ratchet switch 150. The resultant actuation of the armature 159 and the pawl 160 attached thereto causes the ratchet wheel 163 to be rotated counterclockwise through a predetermined angle, thereby moving the contact arm 164 along the resistor

element 165 a predetermined distance counterclockwise. Each such actuation of the armature 157 results in stepwise movement of the arm 164 a predetermined incremental distance counterclockwise along the resistance 165.

Upon occurrence of a high magnitude electrical impulse from the amplifier 130, the threshold device 136 is immediately actuated, permitting the pulse to pass therethrough and through conductors 146 and 147 to the input of the amplifier 149. A portion of the resulting output of the amplifier 149 is applied through conductors 154 and 155 to the windings of the electromagnet 145 of the magnetic switching device 148, causing the armature 144 to move into electrical contact with contact point 143 and thereby place a short-circuit between conductors 140 and 141. That portion of the impulse output from amplifier 130 which passes through the delay device 133 is thus prevented from reaching the windings of the electromagnet 142 of the ratchet switch 150, with the result that meanwhile only the electromagnet 153 is energized through conductors 151 and 152 by the high magnitude impulse. This in turn results in the actuation of the armature 158 and the pawl 168 attached thereto, which in turn results in clockwise rotation of the ratchet wheel 163 through a predetermined angle such as to move the contact arm 164 a corresponding predetermined distance, clockwise along the resistor element 165. Each such actuation of the armature 158 thus moves the contact arm stepwise a predetermined incremental distance clockwise along the resistor element 165.

As hereinbefore described, the resistor element 165 and battery 168 are connected to form a potentiometer circuit such that, as the contact arm 164 moves clockwise, the voltage applied through conductors 167 and 171 to input connections 169 and 172 of the recorder 170 decreases, and, as the arm 164 is moved counterclockwise, it increases. The pen 178 is thus caused to move laterally upon the chart 175 in such a manner that, whenever the voltage across the terminals 169 and 172 decreases, the trace produced by the pen on the chart indicates a decrease in resistivity of the formations, and, conversely, whenever the voltage across the terminals 169 and 172 increases, the trace produced by the pen 178 on the chart indicates an increase in the formation resistivity.

The chart 175 is driven by the depth meter 177 in such a manner that the longitudinal displacement of the chart is synchronously correlated with and represents the depth of the borehole being drilled. (The depthometer illustrated may be constructed in accordance with that disclosed in the application of Jan J. Arps, Serial No. 90,503, filed April 29, 1949.)

As the chart 175 moves synchronously with the downward progress of the drill bit in the borehole, the chart 175 moves in the direction indicated by arrow 176, and the pen 178 plots a graph, as shown at 174, representing the resistivity of the formations, correlated with the depth of the borehole.

Referring now to Figures 9a and 9b, Figure 9a shows a graphical representation of formation resistivity versus borehole depth of a portion of a typical well borehole. The values indicated along the horizontal axis or abscissa of the graph are expressed in terms of ohms/M²/M, and the depth of the borehole is shown in terms of feet from the earth's surface along the vertical axis or ordinate of the graph. The horizontal scale along the abscissa is divided in geometric progression by a series of vertical lines in such a way that the distance to the base line or zero vertical axis of the graph for each successive line is the square root of 2, or 1.414 times the previous distance therefrom.

Figure 9b shows the graph or log curve drawn by a recorder, such as recorder 170, corresponding to the borehole depth and formation resistivity values represented in Figure 9a.

The hereinbefore-described signalling apparatus, including the network of resistances R_0 - R_n , r_0 - r_n , and neon

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tubes T_0 - T_n , is adjusted by employing resistors of such values and tubes of such characteristics that whenever the changing formation resistivity appearing opposite the electrodes 25 and 26, as represented by the graph of Figure 9a, crosses one of the vertical lines, either in a direction of increasing resistance or decreasing resistance, the input voltage in the logging circuit as picked up by the electrodes 25 and 26 and amplified by amplifier 45 correspondingly increases or decreases to a value such that the corresponding neon tube is either ignited or extinguished to actuate the switching mechanism to correspondingly fire either a large or a small explosive signal unit.

For example, referring further to Figures 9a and 9b, assuming the graph of Figure 9a and the chart 175 of Figure 9b to be moving upward together in the direction of the arrow 176 relative to a stationary horizontal reference line in the case of Figure 9a and relative to a longitudinally stationary but laterally movable pen, such as pen 178 shown in Figure 1, then at a borehole depth of 5480 feet, as shown in Figure 9a, the formation resistivity, while increasing, passes the 22.6 ohm value, resulting in a corresponding one of the neon tubes being ignited, which in turn induces a positive surge in the secondary winding 62 of the transformer 61. This actuates the ratchet switch 75 to move the contact arm to a new one of the contact points 86, resulting in the firing of one of the large explosive signal units 100, thereby producing a relatively strong signal impulse.

The microphone 111 or 111a at the top of the borehole picks up this strong impulse signal, and the receiving and recording apparatus, as hereinbefore described, translates the impulse into a corresponding lateral movement of the recorder pen 178, as shown in Figure 9b, from a point W midway between the 22.6 ohm and 32 ohm lines to a point X midway between the 32 ohm and 45.2 ohm lines.

Whenever, as, for example, at a borehole depth of 5,491 feet, the formation resistivity, while decreasing, passes the 16 ohm value, a corresponding one of the neon tubes is extinguished, which induces a negative surge in the secondary 62 of the transformer 61 which actuates the ratchet switch 76 to move the contact arm 85 to a new one of the contact points 87, resulting in the firing of one of the small explosive signal units 100, thereby producing a relatively weak signal impulse.

The microphone 111 or 111a picks up the relatively weak impulse signal thus produced, and the receiving and recording apparatus, as hereinbefore described, translates the impulse into a corresponding lateral movement of the recorder pen 178 from a point Y midway between the 22.6 ohm and 32 ohm lines to a point Z midway between the 22.6 ohm and 16 ohm lines. The recorder thus follows in step with the predetermined resistivity values of the formation to plot thereby a curve having a stepped form at all times approximating that of the formation resistivity curve.

The entire log as produced by the recorder, as illustrated at 174 in Figure 1 or Figure 9b, is not an exact reproduction or representation of the values of the actual resistivity encountered in the borehole, as represented by the curve of Figure 9a, since a step-wise actuation of the recorder is effected, as before described, which only approximates these actual, more gradually changing values of the formations. However, by increasing the number of resistivity values, as represented by the number of vertical lines on the graphs of Figures 9a and 9b, at which the signalling apparatus is actuated, the shape of the recorded log curve can be made to approach that of the actual formation resistivity curve as closely and as accurately as desired, although any such increase in fidelity of the recorded log curve requires a correspondingly increased number of explosive signal units to be provided for in the drill collar.

The operation of the apparatus of Figure 6 is as follows:

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A voltage representative of the resistivity of the formations adjacent the electrodes 25 and 26 is applied through conductors 42 and 43 and filter 44 to the amplifier 45, as hereinbefore described. The resultant output of the amplifier 45 is applied across the neon tubes T_0 - T_n and the operation of the neon tubes and the electrical circuits and apparatus leading up to and inclusive of the ratchet switches 75 and 76 is identical to that hereinbefore described in connection with Figure 1. The results of the actuation of the ratchet switches 75 and 76 of Figure 6 differ from those of Figure 1 in that each time the switch contact arm 84 of the ratchet switch 75 is advanced into contact with a new contact point 201a, a Type A signal unit is fired, thereby releasing a Type A signal pellet into the circulating drilling fluid. Whenever the contact arm 85 of ratchet switch 76 is advanced into contact with a new contact point 201b, a Type B explosive signal unit is fired, resulting in the release of a Type B signal pellet into the circulating drilling fluid stream within the borehole.

Whenever the resistivity encountered at the electrodes 25 and 26 is such as to result in either the igniting or extinguishing of the neon tube T_2 , the resulting sudden change in potential appearing across the resistor 185 is applied through conductors 186 and 187 to the input of amplifier 189. The resultant output of amplifier 189 is applied through conductors 190 and 191 to the rectifier 192, and the rectified D.-C. pulse therefrom applied to the windings of electromagnet 194, resulting in turn in step-wise actuation of the ratchet switch 195 to move the contact arm 200 forward into contact with a new contact point 201. Each time the contact arm 200 is advanced to a new contact point 201, a Type C explosive signal unit is fired, resulting in the release of a Type C signal pellet into the circulating drilling fluid stream within the borehole.

The formation resistivity appearing between the electrodes 25 and 26 and at which the neon tube T_2 will be either extinguished or ignited, depending upon whether such resistivity is either increasing or decreasing at the time, may be selected, by adjustment of the resistance network, to have any desired or suitable value. For example, for convenience of illustration, this resistivity value has been chosen as 11.3 ohms/ M^2/M , as indicated by the vertical dash-dot line in Figure 9a.

The location of the resistor 185 in the circuit may also be chosen as required; that is, it may be located in the circuit in series with any other suitable neon tube which is either ignited or extinguished at a formation resistivity value chosen for use as a reference.

The Type A, Type B, and Type C signal pellets thus released into the circulating drilling fluid stream are carried with the circulating drilling fluid to the top of the borehole and discharged therewith through the outlet pipe 24a and through the pipe section 230 to the shale shaker or screening device 252, and there collected by suitable means for reuse in the system.

Each time either a Type A or Type B signal pellet reaches the top of the borehole and is discharged through the outlet pipe 24a and thereby passes adjacent the ionization chamber 220, the radiation from the signal pellet renders the ionization chamber momentarily conductive, which in turn results in a momentary increase in potential difference across the resistor 224. This increase in potential is applied through conductors 225 and 226 to the input of amplifier 130. When a Type A signal pellet passes out through the outlet pipe 24a, a relatively low amplitude impulse is thus supplied to amplifier 130, and when a Type B radioactive signal pellet similarly passes out of the outlet pipe 24a, a relatively high amplitude impulse is applied to the amplifier 130. From amplifier 130 the operation of the electrical circuits and the ratchet switch 150 is identical to that hereinbefore described in connection with Figure 1.

Each time a Type C magnetic signal pellet passes out

of the side outlet pipe 24a and between the opposite ends of the C-shaped core 232 located at the section of the outlet pipe of reduced diameter, as shown at 231, the reactance of the coil comprising the windings 234 around the core 232 is momentarily changed. This momentary change in the reactance of coil 234 results in the momentary unbalance of the alternating current Wheatstone bridge circuit 237. Such momentary unbalance of the Wheatstone bridge results in a corresponding change in the potential appearing across leg 239 thereof, the resulting current from which, rectified by rectifier 246, is applied through conductors 247 and 251 to the windings of the electromagnet 249 of the marker pen 250. Thus, each time a magnetic signal pellet passes between the ends of the C-shaped core 232, the pen 250 is caused to place a reference mark on the chart 175, as shown at 290 in Figure 6 and in Figure 9b.

Therefore, each time the resistivity of the borehole formations encountered by the electrodes 25 and 26 passes a value of 11.3 ohms/M²/M, as indicated by the rectangular-shaped coordinate reference points in Figure 9a, whether such value is reached either while the resistance is decreasing or increasing, the pen 250 is caused to make a reference mark as shown at 290. In this manner, reference marks are applied to the log 174 corresponding to a given predetermined formation resistivity measured by the electrodes 25 and 26, which reference marks serve as a constant check indicative of whether or not the signal-transmitting apparatus within the drill collar is operating in proper step-by-step synchronism with the signal-receiving apparatus at the top of the borehole. If the receiving and transmitting apparatus are not operating in proper synchronism, or not in proper step, the reference marks, as shown at 290, will automatically establish a reference resistivity value to which the log curve 174 may be correlated or corrected at any time.

Advantages of the present invention over other signaling and logging systems utilizing continuous periodic signals, either amplitude or frequency modulated, are: First, only from 10 to 20% of the number of signals are required for the same amount of logging information. Second, only two or three different types of signals are required, thereby making the method and apparatus for differentiating between the various different types of signals relatively simple. Third, signals are transmitted and received only when the transmission of logging intelligence from within the borehole is vital and important, such as, for example, as illustrated in Figures 9a and 9b, between the depth of 5,475 feet and 5,495 feet, where a highly resistant and possible oil-bearing zone is encountered during the drilling, resulting in a relatively large range of resistivities being encountered and requiring a corresponding, relatively large number of signals, whereas, for example, at a borehole depth of from 5,495 feet to 5,605 feet, where only relatively small changes in resistivity of the penetrated formations are encountered over an extensive length of the borehole, relatively few signals are required.

From the foregoing, it is apparent that the system of the present invention, requiring only a limited number of signals per drilling day, makes this well logging system practicable with relatively small numbers of signal units required to be contained within the lower end of the drill stem or drill collar, and these can readily be replenished each time a round trip is made in the borehole.

In Figures 4 and 5, an alternative construction of the explosive signal units is illustrated. Here each of the signal units 101, instead of having the signal unit outlet opening facing laterally outward to discharge into the annular space surrounding the drill collar, as shown in Figures 2 and 3, has the outlet opening arranged to discharge inwardly and upwardly into the central fluid circulation duct within the drill collar. In the latter con-

struction the drill collar is provided with a plurality of rows of radial bores 108 extending through the walls thereof into the circulating duct within the drill collar. Each signal unit body 101 is secured in a bore 108 by means of a threaded plug 109 which is threaded as shown at 260 into the outer enlarged end of the said bore. Each signal unit body 101 carries a curved barrel member 91 threaded at 261 into the inner end of the body 101. The muzzle opening end 262 of the curved barrel 91 is positioned to face upwardly into the fluid duct of the drill collar.

An explosive charge chamber or cartridge chamber 265 is formed in the rearward portion of the body 101, and the chamber is closed at the inner end with a frangible metal diaphragm 266, which is held in place by the inner threaded end of the barrel 91, and a fluid-tight seal is formed therebetween by means of a suitable gasket 267. An ignition filament 88 extends through the chamber 265 between the grounded diaphragm 266 and a suitable electrical contact pin 268, which extends through an insulating bushing 269, the outer end of which is seated centrally in a cup-shaped insulating member, as shown at 270. An insulated lead wire 271 extends from electrical connection with the said outer end of the contact pin 268 laterally through the cup-shaped insulating member 270, and thence through suitable contacting means at 272 and through a suitable lateral passage 273 in the drill collar, and from there, as shown at 90a, into a longitudinal conductor duct 274 which, as before described, extends downward into the signal-generating portion 13a of the drill collar.

A more complete disclosure of signal-generating units of the types shown at 100 in Figures 2 and 3 and at 101 in Figures 4 and 5 is given in the copending application of Jan J. Arps, Serial No. 260,028, filed December 5, 1951, now Patent No. 2,677,790.

It is to be understood that the foregoing is illustrative only, and that the invention is not to be limited thereby, but includes all modifications thereof within the scope of the invention as defined in the appended claims.

What is claimed is:

1. A method for measuring the value of a varying input electric signal comprising: receiving said input signal and in response thereto producing an output signal of a first predetermined characteristic whenever the said input signal, while increasing in value, reaches predetermined, sequentially graduated, different values; producing an output signal of a second predetermined characteristic whenever the said input signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and second characteristics being selectively different from one another; selectively receiving said different output signals; making a measure of the thus received output signals of the first predetermined characteristic; and making a measure of the number of the thus received output signals of the second predetermined characteristic, to obtain therefrom measured values representative of said varying input signal.

2. A method of measuring the value of a varying input signal comprising: receiving said signal and in response thereto producing an output fluid pressure impulse of a first predetermined characteristic whenever the said input signal, while increasing in value, reaches predetermined, sequentially graduated, different values; producing an output fluid pressure impulse of a second predetermined characteristic whenever the said input signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and second characteristics being selectively different from one another; selectively receiving said different output fluid pressure impulses; making a measure of the number of the thus received output fluid pressure impulses of the first predetermined characteristic; and making a measure of the number of the thus received output fluid pressure impulses of the second predetermined characteristic, to

obtain thereby measured values representative of said varying input signal.

3. A method of measuring the value of a varying input signal comprising: receiving said signal and in response thereto producing an output fluid pressure impulse of a first predetermined magnitude whenever the said input signal, while increasing in value, reaches predetermined, sequentially graduated, different values; producing an output fluid pressure impulse of a second predetermined magnitude whenever the said input signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and second magnitudes being selectively different from one another; receiving said output fluid pressure impulses; making a measure of the number of said received output fluid pressure impulses of the first predetermined magnitude; and making a measure of the number of output fluid pressure impulses of the second predetermined magnitude to obtain thereby measured values representative of said varying input signal.

4. A method for measuring at a second location the value of a varying input electric signal occurring at a first location remote from said second location, comprising: flowing a fluid stream from said first location to said second location; receiving said input signal at said first location and in response thereto introducing into said fluid stream adjacent said first location an output signal of a first predetermined characteristic whenever the said input signal, while increasing in value, reaches predetermined, sequentially graduated, different values; introducing into said fluid stream adjacent said first location an output signal of a second predetermined characteristic whenever the said input signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and second characteristics being selectively different from one another, and said introduced output signals being conveyed by said fluid stream from the point of introduction adjacent said first location to the point of reception at said second location; selectively receiving said different output signals at said second location; counting the number of the thus received output signals of the first predetermined characteristic; and counting the number of the thus received output signals of the second predetermined characteristic, to obtain therefrom at said second location a resultant count representative of the value of said continuously varying input signal.

5. A method according to claim 4, in which said output signal of a first predetermined characteristic and said output signal of a second predetermined characteristic are conveyed by the said fluid stream from said first location to said second location.

6. A method of logging a borehole comprising: producing at given depths within said borehole a logging signal having values representative of values of a physical quantity to be measured within said borehole; producing, in response to said logging signal, an output impulse of a first predetermined magnitude whenever the said logging signal, while increasing in value, reaches predetermined, sequentially graduated, different values; producing an output impulse of a second predetermined magnitude whenever the said logging signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and second magnitudes being selectively different from one another, and said impulses being transmitted up through said borehole to the earth's surface; receiving said impulses at the earth's surface and producing therefrom resultant signals having magnitudes corresponding to said impulse magnitudes; differentiating between said resultant signals having magnitudes greater and less than a predetermined value; causing each such resultant signal having a magnitude greater than said predetermined value to move a marking device a predetermined incremental distance in one direction on a chart; causing each such resultant sig-

nal having a magnitude less than said predetermined value to move said marking device a predetermined incremental distance in the opposite direction on said chart, said movements being thereby algebraically added to place said marking device in positions on said chart indicative of the values of said logging signal; and moving said chart relative to and in a direction different from the motion of said marking device and in correlation with the first-mentioned given depths within said borehole, thereby to produce a graphical record of the values of said physical quantity versus borehole depth.

7. Apparatus for measuring the value of a varying input electric signal comprising: means for receiving said input signal; means actuable in response to said input signal for producing an output signal of a first predetermined characteristic whenever the said input signal, while increasing in value, reaches predetermined, sequentially graduated, different values; means for producing an output signal of a second predetermined characteristic whenever the said input signal, while decreasing in value, reaches predetermined, sequentially graduated, different values; said first and second characteristics being selectively different from one another; means for selectively receiving said different output signals; means for measuring the number of the thus received output electric signals of the first predetermined characteristic; and means for measuring the number of output signals of the second predetermined characteristic, to obtain therefrom measured values representative of said varying input signal.

8. Apparatus according to claim 7 and means actuable in response to said input signal for producing an output signal of a third predetermined characteristic whenever the said input signal, while either increasing or decreasing in value, reaches a particular one of said sequentially graduated, different values; means included in the before-mentioned means for selectively receiving said different output signals for selectively receiving said output signals of the third predetermined characteristic; and means for measuring the number of the thus received output signals of the third predetermined characteristic.

9. Apparatus for measuring the value of a varying input signal comprising: means for receiving said signal; means operative in response to said received signal for producing an output fluid pressure impulse of a first predetermined characteristic whenever the said input signal, while increasing in value, reaches predetermined, sequentially graduated, different values; means for producing an output fluid pressure impulse of a second predetermined characteristic whenever the said input signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and said second characteristics being selectively different from one another; means for selectively receiving said different output pressure impulses; means for measuring the number of the thus received output pressure impulses of the first predetermined characteristic; and means for measuring the number of the thus received output pressure impulses of the second predetermined characteristic, to obtain thereby measured values representative of said varying input signal.

10. Apparatus for measuring at a second location the value of a varying input electric signal occurring at a first location remote from said second location, comprising: means for flowing a fluid stream from said first location to said second location; means for receiving said input signal at said first location and in response thereto introducing into said fluid stream adjacent said first location an output signal of a first predetermined characteristic whenever the said input signal, while increasing in value, reaches predetermined, sequentially graduated, different values; means for introducing into said fluid stream adjacent said first location an output signal of a second predetermined characteristic whenever the said input signal, while decreasing in value, reaches predeter-

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mined, sequentially graduated, different values, said first and second characteristics being selectively different from one another, and said introduced signals being conveyed by said flowing fluid stream from the point of introduction adjacent said first location to the point of reception at said second location; means for selectively receiving said different output signals at said second location; means for counting the number of the thus received output signals of the first predetermined characteristic; and means for counting the number of the thus received output signals of the second predetermined characteristic, to obtain thereby at said second location a resultant count representative of the value of said continuously varying input signal.

11. Apparatus according to claim 10, and mechanical means for subtracting the thus received output signals of one predetermined characteristic from the thus received output signals of the other predetermined characteristic to obtain a difference therebetween representative of the value of said continuously occurring input signal.

12. Apparatus for logging a borehole comprising: means for producing, at given depths within such a borehole, a logging signal having values representative of values of a physical quantity to be measured within said borehole; means for producing, in response to said logging signal, an output impulse of a first predetermined magnitude whenever said logging signal, while increasing in value, reaches predetermined, sequentially graduated, different values; means for producing, in response to said logging signal, an output impulse of a second predetermined magnitude whenever the said logging signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and said second magnitudes being selectively different from one another, and said impulses being transmitted through said borehole to the earth's surface; means for receiving said impulses at the earth's surface and producing in response thereto resultant signals having magnitudes corresponding to said impulse magnitudes; means for differentiating between said resultant signals having magnitudes greater and magnitudes less than a predetermined value; means for causing each such resultant signal having a magnitude greater than said predetermined value to move a marking device a predetermined incremental distance in one direction on a chart and for causing each such resultant signal having a magnitude less than said predetermined value to move said marking device a predetermined incremental distance in the opposite direction on said chart, said movements being thereby algebraically added to place said marking device in position on said chart indicative of the values of said logging signal; and means for moving said chart laterally relative to the motion of said marking device and in correlation with the first mentioned given depths within said borehole, thereby to produce a graphical record of the values of said physical quantity versus borehole depth.

13. Apparatus for logging a borehole during drilling, in which a fluid stream is circulated into and out of the borehole, comprising: means for producing at given depths within such a borehole a logging signal having values representative of values of a physical quantity to be measured adjacent said depths within said borehole; means for releasing into such fluid stream adjacent said depths, in response to said logging signal, an output signal body of a first, pre-

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determined kind whenever said logging signal, while increasing in value, reaches predetermined, sequentially graduated, different values; means for releasing into such fluid stream adjacent said depths, in response to said logging signal, an output signal body of a second, predetermined kind whenever the said logging signal, while decreasing in value, reaches predetermined, sequentially graduated, different values, said first and said second signal bodies being selectively different from one another, and said signal bodies being conveyed by such fluid stream up through said borehole to the earth's surface; means for receiving said signal bodies at the earth's surface and for producing there first and second kinds of output signals in response, respectively, to said first and second different kinds of signal bodies; means for differentiating between said first and second kinds of output signals; recorder apparatus including a movable chart and a marker means for marking on said chart; means for causing each output signal of one kind to move said marking device a predetermined incremental distance in one direction on said chart; means for causing each signal of the other kind to move said marking device a predetermined incremental distance in the opposite direction on said chart, said movements being thereby algebraically added to place said marking device in position on said chart indicative of the values of said logging signal; and means for moving said chart laterally relative to the motion of said marking device and in correlation with the first-mentioned given depths within said borehole, thereby to produce a graphical record of the values of said physical quantity versus borehole depth.

14. Apparatus in accordance with claim 13 in which said signal bodies contain radioactive matter, with those of the first kind having a detectably different degree or radioactivity than those of the second kind.

15. Apparatus in accordance with claim 13, and means for releasing into such fluid stream adjacent said depths, in response to said logging signal, an output signal body of a third, predetermined kind whenever the said logging signal, while either increasing or decreasing in value, reaches a particular one of said sequentially graduated values, said latter signal body also being conveyed by the fluid stream up to the said means for receiving said signal bodies at the earth's surface, and means included therewith for producing, in response to said signal body of said third kind, a third kind of signal different from the before-mentioned different kinds of signals; and another marker means positioned in correlation with the before-mentioned marker means and actuated by said third kind of signal to place a distinguishing mark on said chart upon each occurrence of said third kind of signal.

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