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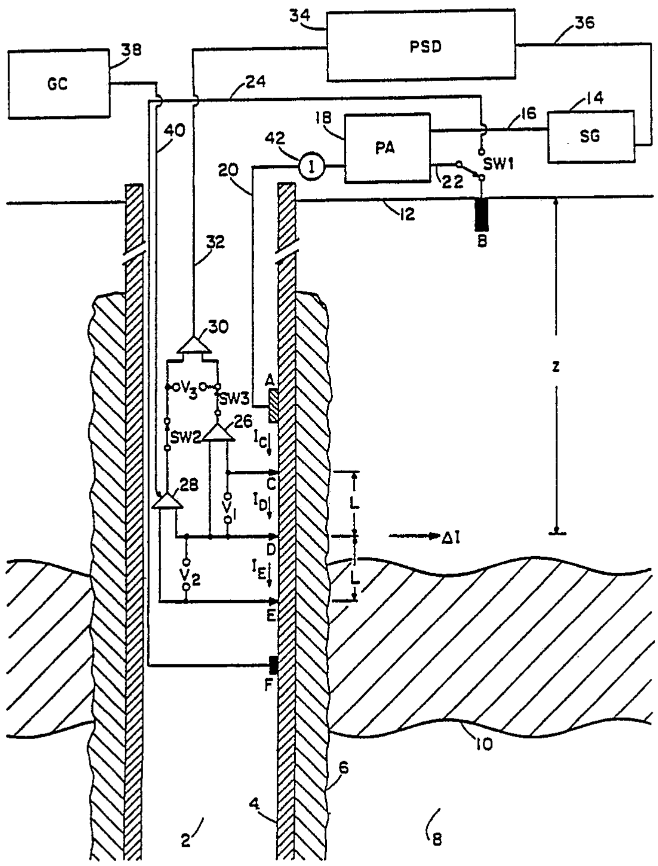
(57) Abstract

An apparatus and method for measuring electrochemical phenomena of formations adjacent a cased well borehole. An alternating current is introduced into the casing (4) in the proximity of the formations to be tested. A portion of the current is received at a point (B) sufficiently remote from the current entry point (A) to ensure that a majority of the current introduced at the current entry point (A) enters the formation along the length of the borehole casing (4). A plurality of at least three spaced apart electrodes (C, D and E) disposed along the interior of the casing detect the voltage level at discrete points along the casing. Calibrated differential voltages between discrete pairs of the electrodes allow inference about electrochemical properties of the formation thereby allowing predictions about the formation composition and/or integrity.



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METHODS AND APPARATUS FOR MEASUREMENT OF ELECTRONIC PROPERTIES OF GEOLOGICAL FORMATIONS THROUGH BOREHOLE CASING

The invention provides methods and apparatus for measurement of electronic properties such as the resistivities, polarization phenomena, and dielectric constants of geological formations and cement layers adjacent to cased boreholes.

Measuring the resistivity of formations adjacent to cased boreholes is important for several reasons. First, such information is useful in locating "missed oil" which is oil in formation which was missed during the original logging operations prior to insertion of the casing. In addition, such information is useful in monitoring water flooding operations during production activities in an oil field.

Numerous U.S. Patents have been issued which address the problem of measuring resistivity through casing. Please refer for example to the following U.S. patents: 2,222,149; 2,224,635; 2,273,363; 2,297,754; 2,397,254; 2,397,255; 2,400,593; 2,414,194; 2,459,196; 2,587,518; 2,729,784; and 2,891,215. It is well known in the industry that so far there has been no method tried which yields the formation resistivity accurately through casing. The above patents all suffer from various problems which have prevented their successful use in the logging industry. Major problems are devising techniques which yield results that are invariant to contact resistances of the electrodes in contact with the casing and which are immune to thickness variations in the casing.

One major problem in measuring formation resistivities in the presence of very conductive borehole casing is that current introduced onto the casing tends to flow primarily on the casing near the current introducing electrodes and ultimately, over long distances, finally flows into formation. Measurement of formation resistivities adjacent to cased boreholes requires methods and apparatus to deal with this problem. Most very early work simply ignored this problem as in the case of U.S. Patent 2,224,635. And in some cases, inventors sought to measure the small effects of current conducted into formation on a large "background signal" due to currents flowing along the casing as exemplified by W.H. Stewart in U.S. Patent Nos. 2,459,196 and 2,371,658 and by J.M. Pearson in U.S. Patent No. 2,587,518. However, measurements of a small signal on top of a large background signal normally lead to poor measurement accuracy. And another attempt was made to solve this problem in U.S. Patents 2,729,784 and 2,891,215 authored by R.E. Fearon which relies upon establishing absolutely equipotential regions along sections of the borehole casing to enable measurements of formation resistivity. The method and apparatus disclosed in the invention requires no such absolutely necessary equipotential surfaces.

The invention has many additional uses. The invention may be used to determine the location of oil/water and oil/gas boundaries. The invention may be used to monitor the integrity of cement behind borehole casing. The invention may also be used to measure polarization phenomena due to the electro-chemical nature of fluids, rock, and cement adjacent to the cased borehole which may be used to infer lithological information about the adjacent geological formation. Furthermore, such polarization measurements may be interpreted to yield measurements of the dielectric constants of fluids in formation which can be used to determine the amount of residual oil and gas in formation. The invention can also be used to determine the dip and strike of the geological formation adjacent to the casing. In conjunction with forcing fluids through formation, the invention may also be used to measure the permeability of geological formations adjacent to cased boreholes. Forcing fluids through formation may also generate fractures of the formation and the invention may be used to monitor the production of such fractures. In addition, the invention may also be used to measure the properties of geological formations through the drill stem attached to a drilling bit while drilling into a geological formation. And finally, the invention may also be used to measure the level of contamination through pipes which penetrate fresh water reservoirs.

Accordingly, an object of the invention is to provide new and practical methods of measuring the resistivity of geological formations adjacent to cased boreholes.

It is yet another object of the invention to provide new and practical apparatus for measuring the resistivity of geological formations adjacent to cased boreholes.

It is yet another object of the invention to provide methods of measuring the resistivity of geological formations adjacent to cased boreholes which are insensitive to the oxidized condition of the borehole casing.

And it is yet another object of the invention to provide apparatus for measuring the resistivity of geological formations adjacent to cased boreholes which are insensitive to the oxidized condition of the borehole casing.

In addition, it is another object of the invention to provide methods and apparatus which allows monitoring of water and chemical flooding of reservoirs during enhanced oil recovery projects.

And it is another object of the invention to provide methods and apparatus which provides a means for monitoring the integrity of a cement layer on the exterior surface of the casing from inside a cased well.

Further, it is still another object of the invention to provide methods and apparatus which allow measurement of electrochemical phenomena collectively identified as polarization phenomena through borehole casing which allows measurement of certain lithological characteristics of the adjacent geological formation such as the difference between clays and sandstones.

And it is yet another object of the invention to provide methods and apparatus which allow the measurement of one type of polarization phenomenon which causes the formation of charges on the exterior of the casing which then allows determination of the dielectric constants of fluids adjacent to the cased borehole which consequently provides a means to differentiate between water present and any oil and gas present, and furthermore, provides a means of measuring the volume occupied by any oil and gas present in formation.

Furthermore, it is yet another object of the invention to provide methods and apparatus which allow the measurement of the permeability of the geological formation adjacent to a cased borehole.

And it is yet another object of the invention to provide methods and apparatus to measure the resistivity of geological formations through a drill stem attached to a drilling bit while drilling into a geological formation.

And further, it is another object of the invention to provide methods and apparatus which allow measurement of the level of impurities present in fresh water formations through pipes which typically penetrate such fresh water formations.

Fig. 1 is a sectional view of one preferred embodiment of the invention of the Thru Casing Resistivity Tool (TCRT).

Fig. 2 is a graph which shows the differential current conducted into formation ΔI for different vertical positions Z of the borehole casing.

Fig. 3 is a sectional view of the preferred embodiment of the invention which shows how the local casing potential V_o is to be measured.

Fig. 4 is a sectional view of an embodiment of the invention which has voltage measurement electrodes which are separated by different distances.

Fig. 5 is a sectional view of an embodiment of the invention which has electrodes which are separated by different distances which shows explicitly how to measure V_o.

Fig. 6 is a plot of ΔI vs. L_3 which is the distance of separation between electrode A and electrode C for a geological formation.

Fig. 7 shows a plot of the total current I_r remaining on the casing vs. L_3 for a geological formation.

Fig. 8 shows a plot of the differential voltage V_3 vs. L_3 for a geological formation.

Fig. 9 shows a plot of V_o vs. L_3 for a geological formation.

Fig. 10 shows a plot of V_3 vs. the frequency of operation f for different currents I_1 and I_2 conducted into formation.

Fig. 11 shows a plot of ΔI vs. the frequency of operation f for different currents I_1 and I_2 conducted into formation.

Fig. 12 shows a plot of V_3 vs. the total current I conducted into formation for various different frequencies of operation respectively f_2, f_4, and f_6.

Fig. 13 shows a plot of ΔI vs. I for various different frequencies of operation respectively f_2, f_4, and f_6.

Fig. 14 shows a plot of V_3 vs. V_o for several different frequencies of operation f_2, f_4 and f_6 respectively.

Fig. 15 shows a plot of ΔI vs. V_o for different frequencies of operation f_2, f_4, and f_6 respectively.

Fig. 16 shows a plot of the phase shift ϕ vs. the frequency of operation f for different currents I_1 and I_2 conducted into formation.

Fig. 17 shows a plot of the phase shift ϕ vs. the total current I conducted into formation for various different frequencies of operation f_2, f_4, and f_6 respectively.

Fig. 18 shows a plot of V_3 vs. time for curves a and b respectively.

Fig. 19 shows a plot of the phase shift ϕ vs. time for curves a and b respectively.

Fig. 20 shows a plot of the quantity ΔI vs. time for curves a and b respectively.

Fig. 21 shows a plot of the phase shift ϕ vs. time for curves a and b respectively.

Fig. 22 shows a sectional view of another embodiment of the invention which requires an additional source of current for measurement.

Fig. 23 shows a sectional view of another embodiment of the invention which minimizes the common mode rejection requirements on the amplifiers.

Fig. 24 shows a sectional view of another embodiment of the invention which shows several different possible ground return paths for the current.

Fig. 25 shows the electrode configuration for another embodiment of the invention which results in a higher order gradient type measurement device.

Fig. 26 shows the electrode configuration for yet another embodiment of the invention.

Fig. 27 shows the top view of an off-axis tool configuration.

Fig. 28 shows the top view of a tool which is centered inside the borehole casing which has 3 electrodes disposed azimuthally around the tool.

Fig. 29 shows the top view of a tool which is capable of measuring voids in cementation through borehole casing.

Fig. 30 shows a method of fabricating electrodes which make electrical contact with the casing while the tool is moving.

Fig. 31 shows a sectional view of an embodiment of the invention used to measure the permeability of a geological formation adjacent to a perforated region of the borehole casing.

Fig. 32 shows a sectional view of another preferred embodiment of the invention which uses an oscilloscope for data measurements.

Fig. 33 shows a sectional view of the preferred embodiment of the invention which shows how V_o is to be measured with an oscilloscope.

Fig. 34 shows a sectional view of another preferred embodiment of the invention which shows how measurements are to be made with a signal averager.

Fig. 35 shows a sectional view of the preferred embodiment of the invention which shows how V_o is to be measured with a signal averager.

Fig. 36 shows a plot of $V_o(t)$ for a particular set of experimental circumstances which is measured with a signal averager.

Fig. 37 shows a plot of the response of $I(t)$ to $V_o(t)$ shown in Fig. 36.

Fig. 38 shows a plot of the response of $V_3(t)$ to $V_o(t)$ shown in Fig. 36.

Fig. 39 shows a plot of the response of $\Delta I(t)$ to $V_o(t)$ shown in Fig. 36.

Fig. 40 shows the voltage output for the power amplifier $V_{PA}(t)$ for one set of experimental circumstances.

Fig. 41 shows a plot of $V_o(t)$ in response to $V_{PA}(t)$ shown in Fig. 40.

Fig. 42 shows a plot of $V_3(t)$ in response to $V_{PA}(t)$ shown in Fig. 40.

Fig. 43 shows a plot of $\Delta I(t)$ in response to $V_{PA}(t)$ shown in Fig. 40.

Fig. 44 shows a plot of the driving current I(t) used for transient response measurements.

Fig. 45 shows a plot of a driving voltage $V_{PA}(t)$ used for transient response measurements.

Fig. 46 shows a plot of another driving voltage $V_{PA}(t)$ used for transient response measurements.

Fig. 47 shows another plot of a driving current I(t) used for transient response measurements.

Fig. 48 shows a sectional view of the invention used to measure formation properties through a drill stem attached to a drilling bit.

Fig. 1 shows a typical cased borehole found in an oil field. The borehole 2 is surrounded with borehole casing 4 which in turn is held in place by cement 6 in the rock formation 8. An oil bearing strata 10 exists adjacent to the cased borehole. The borehole casing may or may not extend electrically to the surface of the earth 12. A voltage signal generator 14 (SG) provides an AC voltage via cable 16 to power amplifier 18 (PA). The signal generator represents a generic voltage source which includes relatively simple devices such as an oscillator to relatively complex electronics such as an arbitrary waveform generator. The power amplifier 18 is used to conduct AC current down insulated electrical wire 20 to electrode A which is in electrical contact with the casing. The current can return to the power amplifier through cable 22 using two different paths. If switch SW1 is connected to electrode B which is electrically grounded to the surface of the earth, then current is conducted primarily from the power amplifier through cable 20 to electrode A and then through the casing and cement layer and subsequently through the rock formation back to electrode B and ultimately through cable 22 back to the power amplifier. In this case, most of the current is passed through the earth. Alternatively, if SW1 is connected to insulated cable 24 which in turn is connected to electrode F, which is in electrical contact with the casing, then current is passed primarily from electrode A to electrode F along the casing for a subsequent return to the power amplifier through cable 22. In this case, little current passes through the earth.

Electrodes C, D, and E are in electrical contact with the interior of casing. In general, the current flowing along the casing varies with position. For example, current I_C is flowing downward along the casing at electrode C, current I_D is flowing downward at electrode D, and current I_E is flowing downward at electrode E. In general, therefore, there is a voltage drop V_1 between electrodes C and D which is amplified differentially with amplifier 26. And the voltage difference between electrodes D and E, V_2, is also amplified with amplifier 28. With switches SW2 and SW3 in their closed positions as shown, the outputs of amplifiers 26 and 28 respectively are differentially subtracted with amplifier 30. The voltage from amplifier 30 is sent to the surface via cable 32 to a phase sensitive detector 34. The phase sensitive detector obtains its reference signal from the signal generator via cable 36. In addition, digital gain controller 38 (GC) digitally controls the gain of amplifier 28 using cable 40 to send commands downhole. The gain controller 38 also has the capability to switch the input leads to amplifier 28 on command, thereby effectively reversing the output polarity of the signal emerging from amplifier 28 for certain types of measurements.

The total current conducted to electrode A is measured by element 42. In the preferred embodiment shown in Fig. 1, the AC current used is a symmetric sine wave and therefore in the preferred embodiment, I is the 0-peak value of the AC current conducted to electrode A. (The 0-peak value of a sine wave is 1/2 the peak-to-peak value of the sine wave.)

In general, with SW1 connected to electrode B, current is conducted through formation. For example, current ΔI is conducted into formation along the length 2L between electrodes C and E. However, if SW1 is connected to cable 24 and subsequently to electrode F, then no current is conducted through formation to electrode B. In this case, $I_C=I_D=I_E$ since essentially little current ΔI is connected into formation.

It should be noted that if SW1 is connected to electrode B then the current will tend to flow through the formation and not along the borehole casing. Calculations show that for 7 inch O.D. casing with a ½ inch wall thickness that if the formation resistivity is 1 ohm-meter and the formation is uniform, then approximately half of the current will have flowed off the casing and into the formation along a length of 320 meters of the casing. For a uniform formation with a resistivity of 10 ohm-meters, this length is 1040 meters instead.

The first step in measuring the resistivity of the formation is to "balance" the tool. SW1 is switched to connect to cable 24 and subsequently to electrode F. Then AC current is passed from electrode A to electrode F thru the borehole casing. Even though little current is conducted into formation, the voltages V_1 and V_2 are in general different because of thickness variations of the casing, inaccurate placements of the electrodes, and numerous other factors. However, the gain of amplifier 28 is adjusted using the gain controller so that the differential voltage V_3 is nulled to zero. (Amplifier 28 may also have phase balancing electronics if necessary to achieve null at any given frequency of operation). Therefore, if the electrodes are subsequently left in the same place after balancing for null, spurious effects such as thickness variations in the casing do not affect the subsequent measurements.

With SW1 then connected to electrode B, the signal generator drives the power amplifier which conducts current to electrode A which is in electrical contact with the interior of the borehole casing. AC currents from 1 amp 0-peak to 30 amps 0-peak at a frequency of typically 1 Hz is introduced on the casing here. The low frequency operation is limited by electrochemical effects also known as polarization phenomena and the invention can probably be operated down to .1 Hz and the resistivity still properly measured. The high frequency operation is limited by skin depth effects of the casing, and an upper frequency limit of the invention is probably 20 Hz for resistivity measurements. Current is subsequently conducted along the casing, both up and down the casing from electrode A, and some current passes through the brine saturated cement surrounding the casing and ultimately through the various resistive zones surrounding the casing. The current is then subsequently returned to the earth's surface through electrode B.

One purpose of the invention is to sense changes in the resistivity of formations adjacent to the borehole and to measure such changes through borehole casing. In many cases, water bearing zones have resistivities of approximately 1 ohm-meter and oil bearing zones have higher resistivities on the order of 10 ohm-meters. The device can measure such a difference through borehole casing, and through brine saturated cement surrounding the casing as is shown by the following analysis.

The downward flowing current below electrode A in Fig. 1 gives raise to a voltage drop along the length of the casing. The voltage along the casing is measured at electrodes C, D, and E respectively where the electrodes are separated by equal lengths L. The resistance per unit length of 7 inch O.D. casing with a wall thickness of ½ inch, r, is given by the following:

$$r = 1.4 \times 10^{-5} \text{ ohms/meter} \qquad \text{Eq. 1}$$

The voltage difference generated by a current I_C at electrode C and I_D at electrode D is approximately the average of the two currents times the resistance per unit length, r, times the length L so that:

$$V_1 = (I_C + I_D)\ rL/2 \qquad \text{Eq. 2}$$

and consequently, V_2 is given by the following:

$$V_2 = (I_D + I_E)\ rL/2 \qquad \text{Eq. 3}$$

The difference between V_1 and V_2 produced by amplifier 30 with switches SW2 and SW3 closed is given by the following (all amplifiers have unity gain for the purpose of simplicity):

$$V_3 = V_1 - V_2 = (I_C - I_E)\ rL/2 \qquad \text{Eq. 4}$$

The net O-peak current, ΔI, flowing into the formation along the length of 2L is given by the following:

$$\Delta I = I_C - I_E = (2\ V_3)\ /\ (rL) \qquad \text{Eq. 5}$$

The resistance R_c of a cylindrical electrode of length 2L and of diameter d in contact with a formation of resistivity ρ is given by the following (<u>Earth Resistances</u>, G.F. Tagg, Pitman Publishing Corporation, N.Y., 1964, p. 96):

$$R_c = \rho\ \text{Ln}\ (4L/d)\ /\ (4\pi L) \qquad \text{Eq. 6}$$

Therefore, if R_c can be measured, then ρ can be computed from Eq. 6 as follows:

$$\rho = 4\pi L\ R_c\ /\ \text{Ln}\ (4L/d) \qquad \text{Eq. 7}$$

The voltage applied to the casing at electrode A causes the casing to achieve a voltage difference V_o between the casing near electrode A and an electrode at infinity as will be discussed shortly. How to measure V_o will also be addressed shortly. The current ΔI flowing into formation from the pipe over the length 2L is also known from Eq. 5, so R_c is experimentally given as follows:

$$R_c = V_o\ /\ \Delta I \qquad \text{Eq. 8}$$

Consequently, the resistivity of the formation adjacent to the borehole over length 2L is given as follows:

$$\rho = 4 \pi L V_o / (\Delta I \text{ Ln } [4L/d]) \qquad \text{Eq. 9}$$

The quantity ΔI is given by Eq. 5, and therefore Eq. 9 becomes the following:

$$\rho = 2 \pi r V_o L^2 / (V_3 \text{ Ln } [4L/d]) \qquad \text{Eq. 10}$$

The experimentally measured parameters are V_o, the voltage applied to the casing at electrode A, the differential voltage V_3 measured with the phase sensitive detector, and I, the O-peak current conducted into formation.

Fig. 2 shows the differential current conducted into formation ΔI for different vertical positions z within a steel cased borehole. z is defined as the position of electrode D in Fig. 1. It should be noted that with a voltage applied to electrode A and with SW1 connected to electrode B that this situation consequently results in a radially symmetric electric field being applied to the formation which is approximately perpendicular to the casing. The electrical field produces outward flowing currents such as ΔI in Fig. 1 which are inversely proportional to the resistivity of the formation. Therefore, one may expect discontinuous changes in the current ΔI at the interface between various resistive zones particularly at oil/water and oil/gas boundaries. For example, curve (a) in Fig. 2 shows the results from a uniform formation with resistivity ρ_1. Curve (b) shows departures from curve (a) when a formation of resistivity ρ_2 and thickness T_2 is intersected where ρ_2 is less than ρ_1. And curve (c) shows the opposite situation where a formation is intersected with resistivity ρ_3 which is greater than ρ_1 which has a thickness of T_3. It is obvious that under these circumstances, ΔI_3 is less than ΔI_1, which is less than ΔI_2.

Fig. 3 shows a detailed method to measure the parameter V_o. Electrodes A, B, C, D, E, and F have been defined in Fig. 1. All of the numbered elements 2 through 40 have already been defined in Fig. 1. In Fig. 3, the thickness of the casing is τ_1 the thickness of the cement is τ_2 and d is the diameter of the casing. Switches SW1, SW2, and SW3 have also been defined in Fig. 1. In addition, electrode G is introduced in Fig. 3 which is the voltage measuring reference electrode which is in electrical contact with the surface of the earth. This electrode is used as a reference electrode and conducts little current to avoid measurement errors associated with current flow.

In addition, SW4 is introduced in Fig. 3 which allows the connection of cable 24 to one of the three positions: to an open circuit; to electrode G; or to the top of the borehole casing. And in addition in Fig. 3, switches SW5, SW6, and SW7 have been added which can be operated in the positions shown. (The apparatus in Fig. 3 can be operated in an identical manner as that shown in Fig. 1 provided that switches SW2, SW5, SW6, and SW7 are switched into the opposite states as shown in Fig. 3 and provided that SW4 is placed in the open circuit position.)

With switches SW2, SW5, SW6, and SW7 operated as shown in Fig. 3, then the quantity V_o may be measured. For a given current I conducted to electrode A, then the casing at that point is elevated in potential with respect to the zero potential at a hypothetical point which is an "infinite" distance from the casing. Over the interval of the casing between electrodes C, D, and E in Fig. 3, there exists an average potential over that interval with respect to an infinitely distant reference point. However, the potential measured between only electrode E and electrode G approximates V_o provided the separation of electrodes A, C, D, and E are less than some critical distance such as 10 meters and provided that electrode G is at a distance exceeding another critical distance from the casing such as 10 meters from the borehole casing. The output of amplifier 28 is determined by the voltage difference between electrode E and the other input to the amplifier which is provided by cable 24. With SW1 connected to electrode B, and SW4 connected to electrode G, cable 24 is essentially at the same potential as electrode G and V_o is measured appropriately with the phase sensitive detector 34. In many cases, SW4 may instead be connected to the top of the casing which will work provided electrode A is beyond a critical depth which will be discussed in detail shortly.

Another issue concerning the operation of the tool is the radial depth of investigation of the tool. The depth of investigation depends upon the distance of separation between the measurement electrodes (the distance L in Fig. 1), the resistivity and geometry of the casing, the resistivity of the adjacent geological formation, and perhaps on the resistivity of remote formations as well. However, since the geometry of the invention resembles focused current arrays used in open holes which have routine radial penetrations of typically 2 feet or more, this tool will have a similar depth of penetration provided that the separations of the electrodes are approximately 1 meter. The distance of separation of the measurement electrodes can obviously be changed to vary the effective radial penetration of the tool for purposes which will be described later.

Certain practical aspects of the design of the tool have so far been neglected because they are common in the industry, and their solutions are also common place in the industry. For example, if the signal is sent to the surface in analogue form over wireline 32 as shown in Fig. 1, then the voltage level from amplifier 30 should be adjusted so that it is large compared to the voltage induced into wireline 32 by downward flowing currents on wireline 20. If this proves to be a problem, then digital communication techniques commonly used in the industry can be employed instead. And in addition, the resistances of the wirelines have been neglected in the analysis, but said resistances produce only relatively small and predictable influences on the operation of the invention. It is assumed that ordinary art in the industry will be employed in the design of the downhole tool.

For the purposes of precise written descriptions of the invention, electrode A is the upper current conducting electrode which is in electrical contact with the interior of the borehole casing; electrode B is the current conducting electrode which is in electrical contact with the surface of the earth; electrodes C, D, and E are voltage measuring electrodes which are in electrical contact with the interior of the borehole casing; electrode F is the lower current conducting electrode which is in electrical contact with the interior of the borehole casing; and electrode G is the voltage measuring reference electrode which is in electrical contact with the surface of the earth.

Furthermore V_o is called the local casing potential. An example of an electronics difference means is the combination of amplifiers 26, 28, and 30. The differential current conducted into the formation to be measured is ΔI, and the differential voltage to be measured is V_3. The measurement state of the apparatus is defined as that state of the apparatus wherein current is conducted from electrode A to electrode B. In the measurement state of the apparatus, electrode F is disconnected from the circuit. And the calibration state of the apparatus is defined as that state of the apparatus wherein current is conducted from electrode A to Electrode F. In the calibration state of the apparatus, electrode B is disconnected from the circuit. It should probably be noted that the calibration state of the apparatus essentially provides a measurement of the resistance of the length of borehole casing adjacent to the formation to be measured which is not substantially affected by the surrounding geological formation.

To further aid in understanding the invention, several preferred embodiments of the apparatus are comprised of several "Fundamental Elements" defined as Fundamental Elements (A), (B), and (C) respectively. Several of the preferred embodiments of the invention are comprised of different combinations of such elements. These elements are defined as follows:

Fundamental Element (A) is a means to cause current to flow from an electrode in electrical contact with the interior of the borehole casing at any depth (electrode A) to an electrode in electrical contact with the surface of the earth (electrode B);

Fundamental Element (B) is at least two pairs of voltage measurement electrodes disposed along the borehole casing which are in electrical contact with the casing (pair CD and pair DE), each pair of said electrodes being the source of a voltage output (V_1 and V_2) resulting from the total current flow between each of the two voltage measurement electrodes and the resistance of the casing between the two electrodes of each pair, and electronics means which takes the voltage difference between the two individual voltage outputs of the individual voltage measurement electrode pairs producing a true differential voltage (output of amplifier 30) which is a direct measurement of the differential current conducted from the casing into the geological formation over the length of the casing between said sets of electrode pairs; and

Fundamental Element (C) is an additional electronics means which produces zero output in the true differential voltage if identical currents are flowing between the electrodes of each voltage measuring electrode pair which happens when current is conducted between two additional current source electrodes which are located on alternate sides of said voltage measurement electrode pairs (such as when current is conducted between electrode A and electrode F when SW1 is connected to cable 24 in Fig. 1) even when the voltage measurement electrodes are separated by different distances and are used in the presence of rusted and corroded casing wherein the resistivity of the casing is expected to be nonuniform. (It will be appreciated that an actual null in the differential output is not necessary, and any other constant number could have been chosen instead, and the data suitably corrected. However, a "zero" for the differential output is simple to interpret.)

The reason why these three different requirements are important depends on an understanding of how current flows on borehole casing as shown in Figs. 1 and 3. Confusion over this fundamental issue has resulted in a number of U.S. Patents which will not provide accurate measurements of formation resistivity through borehole casing. To present this information, it is convenient to define additional distances between electrodes. Fig. 4 is nearly identical to Fig. 1 except the electrodes C and D are separated by length L_1, electrodes D and E are separated by L_2, electrodes A and C are separated by L_3 and electrodes E and F are separated by the distance L_4. In addition, r_1 is the radial distance of separation of electrode B from the casing. And z is the depth from the surface of the earth to electrode D. Fig. 5 is nearly identical to Fig. 3 except here too the distances L_1, L_2, L_3, L_4, r_1, and z are explicitly shown. In addition, r_2 is also defined which is the radial distance from the casing to electrode G. As will be shown explicitly in later analysis, the invention will work well if L_1 and L_2 are not equal. And for many types of measurements, the distances L_3 and L_4 are not very important provided that they are not much larger in magnitude than L_1 and L_2.

The following results are presented for a 7 inch O.D. casing which has a 1/2 inch thick wall which is adjacent to a 1 ohm-meter formation which is infinite in extent and which is uniform. The current I conducted to electrode A is 20 amps O-peak. For the purposes of simplicity in Figs. 4 and 5, let us suppose that $L_1 = L_2 = 1/2$ meter so that ΔI is the current loss per meter into the geological formation. Accordingly, Fig. 6 shows ΔI vs. L_3. Typically, 50 milliamps per meter (mA/m) are lost into the formation in the vicinity of electrode A for a 1 ohm-meter formation. In this analysis $L_3 << z$. For L_3 positive, then electrodes C, D, E, and F are below electrode A. For L_3 negative, electrodes C, D, E, and F are above electrode A which are disposed in the obvious mirror image relationship to the positions shown in Figs. 4 and 5. Fig. 7 shows the current in amps still remaining on the casing (I_r) after a distance of L_3 from electrode A. (In Fig. 7, positive current is defined as current flowing up the casing.) Fig. 8 shows the typical differential voltage V_3 in microvolts per meter (μV/m) for various distances L_3 away from electrode A. And Fig. 9 shows the local casing potential, V_0, in millivolts (mV) for different distances L_3 away from electrode A.

The experimental problem here is measuring the very small current loss of perhaps 50 mA O-peak/meter into the geological formation out of perhaps 10 amps O-peak flowing along the casing. The casing has a resistance of about 10^{-5} ohms/meter, so that the 10 amps O-peak flowing between electrodes C and D would generate a voltage of 100 μv O-peak but the 50 mA O-peak "lost" or conducted into formation between electrodes C and D would produce a voltage difference of only .5 μv O-peak (1 μv = 1 microvolt). A change of .5 μv O-peak out of 100 μv O-peak cannot be accurately measured using only electrodes C and D, particularly since the casing has a variable thickness due to oxidation effects. However, if the voltage difference between electrode pairs CD and DE is taken, then the large "common mode" voltage of 100 μv 0-peak is subtracted out. This is why two sets of electrodes are used to produce a true differential measurement of the current conducted into formation. This is the reason for "Fundamental Element (B)" above in one embodiment of the invention. Most of the prior art does not provide a means to get rid of this large "common mode" signal.

The cause of the current being conducted into formation is the existence of an electric field perpendicular to the casing which points radially outward into the formation. After solving the electrodynamics of this problem, and performing experiments in a salt water tank, it is clear that if electrode B makes good electrical contact with the earth, it's exact position isn't important provided that it is "far away". What happens is that no matter where electrode B is, provided that it is "far away", an electric field exists approximately perpendicular to the casing at depth causing a certain current ΔI to flow into the geological formation along the length 2L of the casing. How the placement of electrode B affects the electric field on the exterior of the casing and the requirement that it be "far away" are addressed further in Fig. 24. However, as long as electrode B is placed in a position such that current flows into the geological formation adjacent to the casing which is energized by electrode A, the invention will function properly. Therefore, the requirement to conduct current into formation is satisfied by "Fundamental Element (A)" of the invention.

"Fundamental Element (C)" of one embodiment of the invention provides immunity to variations in the thickness of the borehole casing. Although this

Fundamental Element (C) may not be absolutely necessary under all circumstances to make the invention functional, it will produce more accurate results than without it. To show why Fundamental Element (C) is important, consider a real problem where the casing is partially oxidized and the electrodes are not separated by equal distances. Suppose electrodes C and D as shown in Figs. 4 and 5 are separated by the distance L_1 and suppose the average resistance per unit length in that portion of the casing is r_1. And similarly, the distance L_2 separates electrodes D and E in Figs. 4 and 5 and that portion of the casing has an average resistance per unit length of r_2. Suppose further that the gains of amplifiers 26, 28, and 30 are respectively a_1, a_2, and a_3 and are calibrated to 2%. And suppose the voltage outputs of amplifiers 26, 28, and 30 are respectively V_{10}, V_{20}, and V_{30}. Initially SW1, is connected to cable 24 as shown in Fig. 4 and current is conducted from electrode A to electrode F. Then, the current I_o is adjusted until V_{30} is equal to a pre-chosen constant K. Then, if SW2 is open:

$$V_{30} = a_1 a_3 r_1 L_1 I_0 = K \qquad \text{Eq. 11}$$

so that:

$$r_1 L_1 = K / (I_o a_1 a_3) \qquad \text{Eq. 12}$$

Now suppose SW2 is closed, and the gain of amplifier 28 is adjusted until $V_{30} = 0$. Then:

$$V_{30} = 0 = (a_1 r_1 L_1 I_o - a_2 r_2 L_2 I_o) a_3 \qquad \text{Eq. 13}$$

or, then:

$$r_2 L_2 = K / (I_o a_2 a_3) \quad \text{Eq. 14}$$

Now suppose SW1 is connected to electrode B, and approximately equal currents are conducted into formation as follows: $\Delta I/2$ between C and D and $\Delta I/2$ between D and E. Using Equations 2 and 3, then V_{30} becomes the following:

$$V_{30} = a_1 a_2 V_1 - a_2 a_3 V_2 \quad \text{Eq. 15}$$

$$= K \Delta I / 2 I_o \quad \text{Eq. 16}$$

And finally, therefore we have ΔI given as follows:

$$\Delta I = 2 V_{30} I_o / K \quad \text{Eq. 17}$$

Measurements of V_o defined in Eq. 8 then allows computation of the resistivity of the adjacent formation using Eqs. 17 and 9. Therefore, even through slightly different lengths of casing where used, which have different resistances per unit length, since I_o is known and K is chosen, ΔI may be accurately measured. This is the reason for "Fundamental Element (C)" of the invention. It should be noted that the resistance per unit length of the casing can probably vary over 30%, and therefore this feature is essential for measuring 50 mA O-peak conducted into formation out of the many amps being conducted along the casing especially if the casing is rusted and corroded. Differences in L_1 and L_2 can be expected in the range of 1% - 5%.

In summary therefore, one embodiment of the invention is succinctly described as a working combination of Fundamental Elements (A) and (B). In addition, another embodiment of the invention may also be succinctly described as a working combination of Fundamental Elements (A), (B), and (C).

As was mentioned previously, the invention measures the resistivity of geological formations directly over a certain frequency interval. At low frequencies, innumerable varieties of electrochemical phenomena collectively referred to as "polarization phenomena" dominate measurements, and can cause extra interpretation problems discerning the resistivity of the formation. And at high frequencies, skin depth limitations of the casing cause difficulties with measurements. These issues will be addressed separately below.

The resistivity measurements in geological formations are predominately influenced by the amount of connate water inside the pores of the rock structure present. This connate water is mostly composed of water and NaCl but numerous other impurities may be present. (See for example, The Properties of Petroleum Fluids, by William D. McCain, Jr., PennWell Publishing Company, Tulsa, Oklahoma, 1973, Chapter 6.) Other relatively minor concentrations of Ca, Mg, SO_4, and HCO_3 are also commonly found along with traces of many other elements and compounds. Therefore, electrical conduction through rock formations is primarily dominated by the electrical conduction by salt water solutions. Any oil present, of course, acts like a relatively insulating fluid. See for example, Essentials of Modern Open-Hole Log Interpretation, John T. Dewan, PennWell Publishing Company, Tulsa, Oklahoma, 1983, Chapter 2. Salt water solutions primarily conduct electricity via chemical reactions which proceed at the anode and cathode respectively of the electrodes at any instant in time. (When electrode A is positive with respect to electrode B, it is an anode, and when negative, it is a cathode. When an A.C. voltage is applied to electrode A, it alternates between being the anode and cathode with the period of the applied voltage waveform.)

Typical anode and cathode reactions responsible for current flow in salt water are described in <u>General Chemistry</u>, by Linus Pauling, W.H. Freeman and Company, San Francisco, Second Ed., 1953, pp. 206-209. The instantaneous anode reaction involves the evolution of oxygen gas as follows:

$$2\ H_2O \rightarrow O_2 \uparrow + 4H^+ + 4e^- \qquad \text{Eq. 18}$$

And the instantaneous cathode reaction involves the evolution of hydrogen gas as follows:

$$2e^- + 2H_2O \rightarrow H_2\uparrow + 2OH^- \qquad \text{Eq. 19}$$

A concern which arises in resistivity measurements is whether the nature of the impurities present affect the dominant type of chemical reactions observed. In fact, Pauling (<u>ibid.</u>) states on p. 208 that "....the electrode reactions are the same for most dilute aqueous electrolytic solutions, and even for pure water as well." However, the resistance to current flow comes from the bulk resistivity of the liquid to ionic conduction under ideal circumstances.

There are various types of electrochemical reactions and processes at electrodes which are collectively described as "polarization phenomena" by various authors. When measuring the current vs. voltage relationships between electrodes in an electrochemical cell (analogous to electrodes A and B in the invention), there are numerous factors to consider in interpreting the data. For example, there are ohmic losses, disassociation voltages, "concentrations overpotential", and, "activation overpotential" effects to consider (Electrochemistry at Solid Electrodes, Ralph N. Adams, Marcel Dekker, Inc., New York, 1969, p. 13). In general terms, concentration overpotential results from non equilibrium distributions of chemical reactants near the electrodes. And the activation overpotential is related to the chemical reactions themselves which may involve the electrode materials. Ralph Adams defines polarization phenomena to include concentration overpotentials and activation overpotentials associated with the electrodes.

It is typical to discuss current vs. voltage relationships between two electrodes in standard chemistry texts. In Electrode Processes and Electrochemical Engineering, authored by Fumio Hine, Plenum Press, New York, 1985, p. 97, the voltage difference between two electrodes in an electrochemical cell is defined figuratively as follows:

$$V_t = E_d + n_a - n_c + IR\ (solution) + IR\ (metal) \qquad \text{Eq. 20}$$

V_t is the voltage output of the cell; E_d is the voltage in the cell in the absence of any current flow; n_c is the "overvoltage" effect for the anode and n_b is the "overvoltage" effect for the cathode; the term IR (solution) is the ohmic voltage drop due to a predominately ionic conduction in the solution; and IR (metal) is the voltage drop due to electronic conduction in the electrodes. It should be stated perhaps that V_t is the output voltage when the cell is forced to conduct current I through it by application of another applied voltage to the cell. For future reference, n_a and n_c shall be called polarization phenomena as well.

In describing current flow between electrodes A and B in Fig. 1, if electrode B is made out of the same material as the casing, and is in contact with a salt solution deliberately mixed up to approximate the salinity of the water downhold, then ideally E_d in Eq. 20 would be zero volts. In any case, it does not change with the applied current and therefore doesn't affect measurements of the resistivity. The term IR (solution) is what the invention is designed to measure and it does so by measuring the ohmic losses in the casing (analogous to IR (metal)). However, the measurement of the resistivity must be performed in such a manner that polarization phenomena do not dominate measurement of the resistivity.

One simple example of a polarization phenomenon is the set of electrochemical processes which result in the formation of gasses on electrodes. In the case at hand, oxygen is formed at the anode and hydrogen is formed at the cathode. If sufficient current densities are conducted from the casing to electrode B, then it is possible that gasses could build up on both the casing and electrode B. Since the polarity is reversed when measuring resistivity (A.C. voltage is used) then the casing acts alternatively as an anode and then a cathode, so that in principle, mixtures of hydrogen and oxygen would appear on the casing in time. Similarly, gasses would form on electrode B. Ultimately, the casing in the vicinity of electrode A and electrode B itself could become covered with gasses. Then, for a given total current of I conducted through formation, ΔI in the vicinity of electrode A and V_3 could become nearly zero since gasses would not permit conduction into the formation near electrode A. Furthermore, for a given total current I, much higher voltages V_o would have to be applied to conduct the same ΔI into formation since electrode B could become entirely covered with gasses. This is an extreme example of a polarization effect related to a concentration gradient, and here, the concentration gradient is caused by gas build-up.

This type of polarization effect is strongly dependent on the current density at the electrode. This is typically the case, and for more information and a plot of this type of overvoltage or polarization effect vs. current density, please refer to <u>Physical Chemistry</u>, Walter J. Moore, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1962, p. 406. In the invention, such an effect would produce non-linear relationships between V_3 vs. I, ΔI vs. I, V_3 vs. V_o and ΔI vs. V_o.

In addition, such a polarization effect would not stay stable in time. Therefore, if a constant current I were conducted between electrodes A and B, V_3 would probably decrease in time. And since this polarization effect is strongly dependent upon the current density, plots of V_3 vs. time for two values of I would again demonstrate that this type of polarization effect was influencing the data.

In addition, if the current conducted through formation is high enough, then it is possible to produce concentration gradients in the NaCl and water near the electrodes. Concentration polarization phenomena are discussed by Walter J. Moore (<u>ibid.</u>), pp. 408-413). Such phenomena are also discussed explicitly for NaCl in water in Adams (op.cit. pp. 3-11). Such phenomena would affect resistivity data in similar non-linear fashions as described above. And in addition, many other polarization type phenomena are discussed by example in Industrial Electrochemistry, Derek Pletcher, Chapman and Hall, New York, 1982, Figure 1.1. Please also refer to The Chemistry of Electrode Processes, by Ilana Fried, Academic Press, New York, 1973, p.22, for another list of "overvoltage" or polarization phenomena.

In addition, the orientation of the polar water molecules in the applied electric field from the casing and electrode B certainly would also be described as another class of polarization phenomena. Such effects can be effectively described in terms of the capacitance of electrodes in the presence of dielectric materials. For a clear explanation of such phenomena, the reader is referred to Physics for Students of Science and Engineering, Part II, authored by David Halliday, et al., John Wiley & Sons, Inc., New York, Second Edition, 1962, Sections 30-3, 30-4, 30-5, 30-6, and 30-7. In such cases, dynamic polarization effects are larger at lower frequencies since low frequencies provide longer "alignment times" which could be used to distinguish this effect from others.

In general, many polarization phenomena result in non-linear relationships between V_3 or ΔI vs. either V_o or I. And all other things being equal, polarization phenomena are larger at lower frequencies because such low frequencies allow polar molecules to orient in applied fields, allow for preferential gas build-up on the electrodes, and also allow the time necessary to produce concentration gradients in solution. At higher frequencies on the other hand, the skin effect of the casing interferes with the interpretation of the resistivity data.

As the frequency of the current I is increased, then eventually a frequency will be reached when most of the current simply flows from electrode A up the inside of the casing to the surface for a return to electrode B. This is caused by the skin effect of the pipe. The skin effect causes an exponential attenuation of the electric field applied across the thickness of the steel casing, where the electric field is attenuated as follows:

$$\xi = \xi_o e^{-(\tau_1 / \delta)} \qquad \text{Eq. 21}$$

The electric field ξ_o is that applied to the inside of the casing by electrode A, ξ is the field immediately outside the pipe, τ_1 is the thickness of the pipe, and δ is the skin depth given by the following:

$$\delta = (\pi \ f \ u \ \sigma)^{-1/2} \qquad \text{Eq. 22}$$

Here, f is the frequency in Hz, μ is the magnetic permeability, and σ is the conductivity of the material. (Please refer to <u>Fields and Waves in Communication Electronics</u>, Simon Ramo, et al., Second Edition, John Wiley & Sons, 1984, p. 149) Typical steel in borehole casing has a relative permeability of 100, and the resistivity ($1/\sigma$) of typical steel is 10 micro-ohm-cm. Therefore the above formula becomes:

$$\delta = (.62/ f^{1/2}) \text{ inches} \qquad \text{Eq. 23}$$

The critical frequency is the frequency where the skin depth equals the thickness of the pipe in question. The critical frequency for a .50 inch wall thickness if 1.54 Hz. The critical frequency for a .375 inch wall thickness is 2.73 Hz. Typically, casing has wall thicknesses between .25 and .50 inches. If the frequency of operation is significantly less than the critical frequency, then the results for resistivity measurements need not be corrected for skin depth phenomena. For frequencies above the critical frequency, then the resistivity results need to be corrected for such phenomena. For very high frequencies of operation, then none of the current is conducted through the pipe into the formation but instead goes up the inside of the pipe from electrode A for a return across the earth's surface to electrode B. Therefore, under such circumstances, no matter how much total current was conducted between electrode A and electrode B, V_3 would be very small. (As a related subject, but which is only incidental here, it should also be apparent that skin effects in the geological formation and perhaps in the borehole fluids may also be observed, but calculations show that these effects are minor compared to the influence of the casing on high frequency operation.)

The following figures are presented to diagrammatically depict hypothetical situations which may be encountered during the measurement process. The figures depict the interrelationship between basically four variables: ΔI, the differential current conducted into the adjacent geological formation; V_3, the differential voltage to be measured due to the conduction of ΔI into formation; V_0, the local casing potential; and I, the total current conducted into the geological formation along the entire length of the casing in the measurement state of the apparatus. Fig. 10 shows a plot of V_3 vs. the frequency f for several values of the 0-peak current conducted downhole, for I_1 and I_2. For I_1, f_1 is still in a region dominated by polarization effects, f_3 is the lowest frequency where polarization effects are relatively negligible compared to resistivity effects, f_4 is in the center of the frequency band appropriate for resistivity measurements, f_5 is the uppermost frequency where resistivity effects dominate skin-depth effects of the casing, and f_6 is in a region where skin-depth effects dominate the measurements. For current I_1, resistivity measurements should be performed in the region where V_3 is ideally a relative constant, namely between frequencies f_3 and f_5. For I_2 which is a larger current conducted through the formation, the relative shape of the curve can change significantly in the polarization region. Here, at f_2, dynamically moving polar water molecules actually increase V_3 to larger values than would otherwise be observed. However, accurate resistivity data can still be taken between frequencies f_3 and f_5 for current I_2. Fig. 11 is nearly the same as Fig. 10 except here the quantity ΔI is plotted vs. the frequency f. However, the major conclusions are all the same.

Fig. 12 shows a hypothetical plot of V_3 vs. I for the different frequencies f_2, f_4, and f_6. The data at frequency f_4 shows the proper linear behavior for resistivity data. The data at frequency f_2 shows complicated behavior due to various polarization effects, and the data at frequency f_6 is influenced by skin depth effects. Fig. 13 shows a similar plot except here the quantity ΔI is plotted vs. the current I for different parameters of the frequency f_2, f_4, and f_6. Fig. 14 is a similar plot, except here V_3 is plotted v. V_0 for the various different frequencies. And Fig. 15 is another similar plot, except here the quantity ΔI is plotted vs. V_o for the different frequencies.

In addition, the phase sensitive detector 34 in Fig. 1 has, in principle, a magnitude output and a phase output corresponding to the amplitude and relative phase of the signal. In fact, the phase of the signal is referenced against the output from the signal generator through cable 36 in Fig. 1. Therefore, the phase of the signal can be measured in relationship to the phase of the driving voltage V_o, or the driving current I using standard techniques with phase sensitive detectors. (To measure the phase of the current I, a series resistor inserted inside element 42 can yield a suitable voltage source to allow phase measurements of I with respect to the signal on cable 36. Then, using the arrangement in Fig. 3, the phase of V_o with respect to the signal available on cable 36 can be determined. Then the relative phase of both I and V_o may be determined. The phase of V_3 can then be determined in relation to I and V_o.) There are many manufacturers of suitable phase sensitive detectors, and one is EG&G Princeton Applied Research Corporation, Princeton, New Jersey, U.S.A.

Fig. 16 shows the hypothetical phase shift ϕ between V_3 and V_o vs. frequency for two different currents, I_1 and I_2. Between f_3 and f_5, the phase shift is zero, and therefore this frequency interval is ideally suitable for resistivity measurements. For frequencies below f_3, different currents produce different phase shifts as may be the case for various different types of polarization phenomena. And at high frequencies, such as f_6, skin depth phenomena affect the data, but at least such effects are not critically dependent upon the current (although the permeability of the steel casing could also be a function of the current, thereby causing different phase shifts for different currents).

Fig. 17 shows a plot of the phase shift between V_3 and V_o vs. the current I for three different frequencies. At frequency f_4, standard resistivity data can be taken. At frequency f_6, the skin depth of the casing introduces a constant phase shift between V_3 and V_o. And finally, at f_2, different polarization phenomena at different current strengths are evident.

In addition, once a measurement of V_3 is started, it should not change in time. If it does, then this could be due to gas build up or other polarization type phenomena. For example, Fig. 18 shows V_3 vs. time for a hypothetical situation where curve (a) shows standard resistivity type results, and curve (b) shows the influence of time dependent polarization phenomena. Fig. 19 shows the phase difference between V_3 and V_o vs. time. In curve (a), a standard resistivity measurement is indicated, and in curve (b), polarization effects are becoming more important in time.

Of course, the quantity ΔI vs. time should not change for resistivity type measurements either. Curve (a) in Fig. 20 shows ΔI vs. time for a case of standard resistivity measurements, and curve (b) shows data where polarization effects are becoming important. And lastly, curve (a) in Fig. 21 shows the phase shift ϕ between ΔI and V_o for standard resistivity measurements, and curve (b) shows data for the case where polarization effects are influencing the data.

For future discussions, a measurement is in the "resistivity region" if the measurements primarily result in measurements of the resistivity of the geological formation. And measurements are in the "polarization region" wherein the measurements are significantly affected by polarization effects. And measurements are in the "skin effect region" if influenced strongly by the skin depth of the casing.

As previously stated, one embodiment of the invention is succinctly described as a working combination of Fundamental Elements (A) and (B). In addition, another embodiment of the invention may also be succinctly described as a working combination of Fundamental Elements (A), (B), and (C). In addition, the invention also includes functional replacements for Fundamental Elements (A), (B), and (C) which perform the same tasks, but which have different mechanical and electronic configurations. For example, the essence of this invention is that it allows measurement of the "current lost" (current conducted) into formation along a precisely defined length of borehole casing analogous to the quantity ΔI described so far under the application of an A.C. electric field which has a component substantially perpendicular to the casing. This measurement allows a direct measure of the formation resistivity. The methods used to directly measure the current ΔI include sensing voltage drops along the casing after an initial null is achieved as shown in Fig. 1 but may include other methods which basically measure the same parameter ΔI, but which involve introducing current on the casing to achieve said measurement. For example, another embodiment of the invention is shown in Fig. 22. Here all the elements have been defined in Fig. 1 with the exception that an additional variable resistor R is connected to cable 20 which is in turn connected to a current measurement device 44 which measures the current I_z conducted to electrode F. In this case, after null is achieved in the calibration state of the apparatus, extra A.C. current I_z (O-peak) is introduced at electrode F and adjusted until there is a null voltage output for V_3. At this point, the current I_z introduced on the casing is related to the current lost between electrodes C and E. However, this is just another means to measure the current lost into formation along a precise length of borehole casing under application of an A.C. electric field which is substantially perpendicular to the casing. And in addition, any number of similar current introducing elements may be also attached to electrodes C, D, and E which will also allow measurement of ΔI.

In addition, Fig. 23 shows another embodiment of the invention. This embodiment relaxes the "common mode rejection" requirements on amplifiers 26 and 28. Here additional electrodes are attached to electrodes A and F and are labeled A′ and F′ respectively in Fig. 23. The distance L_5 and L_6 are defined on the drawing. An extra "pole" has been added to SW1 shown in Fig. 1 and here it is a double-pole-double-thro type switch which performs it's original function in Fig. 1 with SW1A and in addition, performs another function with SW1B. In this case when SW1A connects cable 22 to electrode B in the measurement state of the apparatus, then SW1B also connects electrodes F and F′ to electrodes A and A′. This means that the region between electrodes A and F is nearly an equipotential with little net current flowing along the casing between electrodes A and F but as in Fig. 1, current is still lost into formation between electrodes C, D, and E as shown.

The advantage of this arrangement is that the common mode voltages appearing across the inputs of amplifiers 26 and 28 are reduced in magnitude from Fig. 1. In this case, it may not prove necessary to "balance" the electronics for null in the calibration state of the apparatus as described in Fig. 1 to achieve reasonable measurements of ΔI. However, such initial nulling would still improve the overall accuracy of the measurement under realistic borehole conditions. In addition, many of the concepts used for the "focused current electrodes" used in open boreholes could be used here in determining the placement of electrodes like A and A′ and F and F′ for example. Of course, the natural cylindrical geometry of the casing "focuses" the current naturally - namely it helps to cause deep radial penetration by the current. (For information concerning focused current arrays used in open holes, please refer to the Encyclopedia of Well Logging, Robert Desbrandes, Gulf Publishing Company, Houston, Texas, 1985, p. 117.) Any number of electrodes such as electrode A, A′, etc. could be made to contact the casing for various different purposes. And, of course, electrodes A′ and F′ in Fig. 23 could be removed and the invention would still work nearly as well. An extra complication with this embodiment of the invention is the necessity to determine the current flowing independently in each segment of the casing between the measurement electrodes which may be accomplished in an obvious manner using the "invert" command sent to amplifier 28 by the gain controller which inverts the input leads to amplifier 28 for these measurements. It should also be noted that Fig. 23 shows electrodes A and A′ which are used for two purposes: to conduct current into formation in the measurement state of the apparatus and to pass calibration current to electrodes F and F′ in the calibration state of the apparatus. It should be evident that separate electrodes could be used for each separate function, although combining functions in one electrode minimizes complexity of the downhole tool. Also, electrode A or A′ can be placed between electrodes C and D in another embodiment of the invention.

Fig. 24 shows another embodiment of the invention. The purpose of Fig. 24 is to present various alternatives for the placement of electrode B and to further discuss requirements which electrode B must satisfy for proper operation of various embodiments of the invention. Here, most all of the elements have been defined in Fig. 1 except here SW1C replaces SW1 in Fig. 1. Switch SW1C may be used to connect to alternative grounding positions shown figuratively as B, B_1, B_2, and B_3 in Fig. 24. Electrode B has already been described. B_1 is an electrode in electrical contact with the interior of the casing which is located beyond a critical distance, L_c, away from electrode A. As long as the length of casing between A and B_1, L_8, is comparable to or larger than L_c, then the electric field is primarily perpendicular to the casing when electrode A is energized, and the invention works in the usual fashion. The critical distance L_c is that length of casing adjacent to a formation where the series resistance to current flow equals the contact resistance of the pipe adjacent to the formation. (For a uniform formation, that distance can be calculated by requiring that at a particular length L_c, the series resistance to current flow along the length L_c of the casing which is given by the algebraic expression ($L_c r$), where r is defined in Eq. 1, is equal to the resistance R_c in Eq. 6 for the particular length $L_c/2$. This equation is then solved for the length L_c. This is also the approximate distance where half of the current flows off the casing into the formation which has already been discussed). The requirement on the length of L_8 is a matter of convenience only, because for shorter lengths of L_8, as long as the placement of electrode B_1 is such that it allows the generation of any significant component of the electric field perpendicular to the casing in the vicinity of electrode A, then current is conducted into formation from the casing adjacent to electrode A, and the invention functions properly. In addition, B_2 is an electrode in electrical contact with the top of the borehole casing. Here too, as long as the resistance of the length of casing between A and B_2 is comparable to or larger than the total resistance to current flow between electrode A and electrode B, then the electric field is primarily perpendicular to the casing when electrode A is energized, and the invention works in the usual fashion. And finally, B_3 is another earth ground, and it's position is immaterial provided that the electric field produced on the exterior of the casing is primarily perpendicular to the casing which will allow proper measurement of the resistivity of the geological formation. Although the electric field is primarily perpendicular to the casing at great depths independent of the position of the ground return (B, B_1, B_2, or B_3), there none-the-less should be small detectable differences related to the different current paths. Therefore, different grounding returns could provide a means of measuring the resistivity of different selected portions of the formation such as the resistivity of different quadrants. Such measurements are only a minor modification of the invention.

In addition, a higher-order gradient measurement can be performed wherein one set of vertically disposed electrodes A, C, D, E, and F as defined in Fig. 1 is at one vertical position and then another corresponding set of electrodes A'', C'', D'', E'', and F'' are located at a different vertical position. Please refer to Fig. 25 which shows the functionality of the higher order gradient type device. The voltage output from the first set of electrodes is V_3 and from the second set of electrodes is V_3''. Differences between V_3 and V_3'' are then measured which provide a different type of gradiometer for vertical sections of the formation. Here, differential amplifier 46 takes the voltage difference between V_3 and V_3'' which produces V_{out} which is the output voltage of the higher-order gradient measurement device. As is obvious, additional sets of electrodes A''', C''', D''', E''', and F''' could also be added in an analogous fashion and the output V_3''' could be compared to the other two outputs to infer information about the geological formation.

Fig. 26 also shows another embodiment of the invention in a figurative fashion. Here electrodes A and F are current conducting electrodes as defined in Fig. 1. However, here voltage measurement electrodes k, l, m, n, o, p, q, r, s, and t are disposed vertically between electrodes A and F. They each provide a voltage difference between adjacent pairs such as V(k,l), V(l,m), V(m,n), V(n,o), V(o,p), V(p,q), V(q,r), V(r,s), and V(s,t). The appropriate voltage differences along the length of the borehole casing may be processed by analogue circuitry or may be digitized and analyzed in various fashions to eliminate various errors. Such errors may include bogus signals due to stray currents in the fluid inside the cased borehole and capacitative voltage pick-up from the energized wirelines, and such stray signals may be minimized by using one or more of the following voltage processing schemes. For example, the voltage difference between electrodes k and o, V(k,o), may be directly measured. However, this voltage V(k,o) is also equal to the following:

$$V(k,o) = V(k,l) + V(l,m) + V(m,n) + V(n,o) \qquad \text{Eq. 24}$$

Processing the signal in this manner may eliminate various types of errors such as voltage pick-up, etc. Alternatively, the signal V(k,o) could be processed as follows:

$$V(k,o) = [V(k,l) + V(m,n)] + [V(l,m) + V(n,o)] \qquad \text{Eq. 25}$$

Such processing would eliminate different sorts of pick-up and other types of systematic measurement errors. And in addition, adjacent measurement pairs need not be used to perform the measurements. For example, the resistivity of the formation could be determined easily between points k and r by computing the following:

$$V(k,l) - V(m,n) - (V[o,p] - V[q,r]) \qquad \text{Eq. 26}$$

And, of course, another set of such electrodes could be added below the described sets of electrodes which could be labeled as follows: A'', k', l', m', n', o', p', q', r', s', t', and F'' which could be operated to measure the resistivity of adjacent formations as well.

As another application of the invention, vertical arrays of electrodes can be used to look for horizontal cement voids behind casing. If cement is missing from behind the casing, that space is generally filled with fluids which are relatively conducting and consequently more current will conduct preferentially into the relatively conducting areas. Vertical arrays of electrodes as shown in Fig. 26 are ideally suited for locating horizontal voids in cement behind casing. However, the distance between adjacent electrodes for such measurements should obviously be less than the radius of the pipe. In fact, as long as the cement void is filled with fluids which have resistivities different than the geological formation, then such methods will work to find horizontal cement voids. Locating such voids is important to maintain casing integrity and is of importance to the oil industry and may ultimately provide a major use for the invention.

The voltage measurement electrodes, typified by electrode C in Fig. 1 may have many different methods of fabrication. The tool may be an off-axis tool, where the tool body presses against one side of the casing. Please refer to Fig. 27 which shows a top view of the tool. Here the borehole casing is labeled 4, the cement is 6, the geological formation is 8 and the tool body or "sonde" is 48, and it has just one electrode extending from the tool corresponding to electrode C. This electrode may extend from the tool using motor drives, hydraulic drives, or other methods which are standard in the industry. Similarly, electrodes A, D, E, and F may also have just one contact point with the casing. Each electrode may be encapsulated in rubber which pushes back from the electrode when the electrode contacts the casing but whereby the rubber otherwise electrically insulates the electrode from the borehole fluids.

Fig. 28 shows the top view of a symmetrically centered borehole tool. The tool shown has three individual electrodes corresponding to electrode C: C1, C2, and C3. And in addition, electrode A has individual electrodes A1, A2, and A3; electrode D has electrodes D1, D2, and D3; electrode E has individual electrodes E1, E2, and E3; and lastly, electrode F has individual electrodes F1, F2, and F3. The electrodes are fabricated such that electrodes A1, C1, D1, E1, and F1 are all in "line" vertically. Therefore, different quadrants of the formation may be investigated around the borehole using different oriented sets of electrodes. For example, electrode set A1, C1, D1, E1, and F1 can be independently measured using the techniques outlined in Fig. 1. Then, similarly, electrodes A2, C2, D2, E2, and F2 can be independently configured a shown in Fig. 1. And lastly, electrodes A3, C3, D3, E3, and F3 can also be used for another independent measurement. Such measurements performed at different angular orientations along a vertical section of pipe can be used to investigate different angular quadrants of the formation. Measurements in different angular quadrants may be of significant interest because, for example, a salt dome may be adjacent to a cased hole in one quadrant which contains oil, and that may be the target of exploration. And in addition, such measurements provide independent measurements of the dip ("tilt") and strike (direction of the "tilt") of the formation which are important geophysical quantities. Such a dip and strike tool would also necessarily have to be provided with a means to determine the relative orientation of the tool within the borehole.

Another embodiment of the invention is shown in Fig. 29. Here, electrode C has a total of 16 different contacts. However, each individual contact is brought into the interior of the tool housing with an insulated wire for measurement. Similarly electrode D has 16 such electrodes and so does electrode E. However, in this embodiment, voltage differences are not taken between vertically disposed electrodes but instead are taken between horizontally disposed electrodes. Therefore, the voltage differences are taken between adjacent pairs of electrodes, for example between the following pairs of electrodes: C2-C1, C3-C2, ... C-16-C15, and C-1-C16. Similar differences are taken for electrode D and electrode E. If the cement is uniform around the casing and the geological formation is horizontally homogenous, then there will be no differences in the above measurements. However, suppose there is a void in the cement as shown by the shaded region 50 in Fig. 29. In this case, the void will probably be filled with relatively conducting water, and more current will flow out of the casing along this preferential direction. Therefore, in this case the differential current per unit area ΔJ_1 conducted through the cement is smaller than the current per unit area ΔJ_2 conducted through the water as shown in Fig. 29. Sometimes there are vertical groves in the cement, and vertical groves would yield similar measurements using electrodes D1....D16 and E1....E-16. Determining the presence of voids in concrete behind casing is of considerable importance to the oil industry. Therefore, this embodiment of the invention could attain widespread use for this reason alone.

Also notice in the above description of the invention, that the electrodes can be fabricated such that electrodes C1, D1, and E1 are all in a row vertically. Similarly electrodes C10, D10, and E10 would also be in a line vertically. Therefore, since the insulated wires attached to each individual electrodes are brought into the electronics housing, electronic means can be provided to first take a series of horizontal voltage differences, and then a series of vertical voltage differences. Consequently, three dimensional information about where the current is flowing and information concerning the presence or absence of cement voids behind casing would thus be attained. Basically, the invention contemplates using any number of voltage sensing electrodes in electrical contact with the interior of the borehole casing to measure the differential current conducted into formation between any number of pairs of said electrodes to infer the resistivity and changes in resistivity of the adjacent geological formation and to infer the presence or absence and/or the integrity of the cement around the borehole casing. Therefore, any array of electrodes which are disposed in any manner inside the casing may be suitably chosen for measurements of the differential current conducted into the adjacent formation. And as already stated, such measurements can yield the dip and strike of the geological formation if the borehole tool is also provided with a means to determine the orientation of the electrodes with respect to the borehole casing by using devices such as a gyroscope or suitable magnetic field measurement device.

In all the embodiments of the invention, the electrodes are pictured to make physical contact with the casing. For example, electrodes A, C, D, E, and F are shown in the figures to actually make physical contact with the borehole casing. However, if the borehole is filled with relatively conducting fluids having resistivities comparable with formation resistivities, then these electrodes need not actually touch the borehole casing. In fact, "banded electrodes" as described in U.S. Patent No. 2,891,215 may work well under these circumstances. In addition, if it is found that electrodes must actually physically contact the casing but also have the capability to move vertically, then electrodes can be fabricated which resemble the movable electrodes described by W.H. Stewart in U.S. Patent 2,371, 658. Many different types of electrodes which move and make suitable electrical contact are possible.

One method of fabricating a movable electrode is shown in Fig. 30. The casing 4 is shown and so is the tool housing 48. A rotating cutter electrode 52 made from hardened tool steel is held against the casing with a spring loaded insulated arm 54 and the electrical signal is conducted into the electronics housing within the tool using insulted wire 56. The entire cutter assembly is surrounded with a hard rubber structure 58 which tends to insulate the cutter electrode from extraneous electric fields which may be present in the fluid inside the borehole casing. In addition, a scraping device 60 precedes the rotating cutter electrode as the tool is drawn vertically and clears debris 62 off the inside of the casing wall which is helpful in making better electrical contact with the rotating cutter electrode.

It is also standard practice in the oil industry to use log-inject-log techniques wherein a formation is first logged, then fluids are forced into the formation to be measured, and then measurements are performed after said fluids replace the formation fluids originally in place. Sometimes measurements are performed during the actual fluid injection process. Please refer to Fig. 31. Pump 64 obtains fluids through pipe 66 attached to a large fluid reservoir 68 which contains fluids 70. Fluids are then forced under pressure through pipe 72 to a combination pressure meter and flow meter 74 and then through pipe 76 into the top of the well bore. Pipe 76 is often called production tubing which may be suspended in place using various different techniques. Pressure fitting 78 prevents pressurized fluids from escaping from the well bore. Since a plug 80 is below the perforations 82 in the borehole casing near a producing zone (or a test zone), fluids are forced into the formation through the perforations. The various conductors 20, 24, 32, and 40 are contained inside an armored wireline 84 which is customary practice in the industry (and not explicitly shown in the prior figures). This wireline supports the weight of the sonde and slides through the pressurized grease fitting 86 which prevents fluids from escaping from the well bore under pressure.

With a known quantity of fluid injected into place from measurements obtained with the combination pressure meter and flow meter 74, and with the resistivity of fluids 70 known and chosen with substantially different resistivities than fluids present in formation, then the changes in the resistivity of the formation can be measured vs. the amount of fluid pumped into formation. This data can be used to determine the resistivity of fluids naturally in place, the amount of residual oil in place, information about oil/gas interfaces, the porosity, and the permeability of the geological formation using methods of analysis typical in the industry. A typical situation would be choosing fluids 70 which are much more conducting than either the connate water in place or certainly the oil in place, and measurements performed during or after the injection process. Salt water solutions are, of course, obvious choices for the injected fluids among the other standard choices for fluids in the industry. In addition, the pressurized fluids injected into formation may be used to actually fracture the formation itself, and the invention can be used consequently to determine the quantity and direction of the fractures produced.

Similarly, the invention can be used to simultaneously measure the changes in formation resistivity inside one well while fluids are being simultaneously pumped into the geological formation from at least one additional well in the general vicinity. This is a variation of the invention shown in Fig. 31 wherein the source of injected fluids comes from a different well in the oil field. And finally, normal production activities involve the removal of fluids, and measurements while producing can lead to an understanding of how fluids are moving in the oil field under actual production activities which is another use of the invention.

To this point, it has been emphasized that the measurements are being interpreted solely for resistivity data. However, the same apparatus can be used to measure polarization phenomena. All things being equal, as discussed previously, lower frequencies and higher currents will emphasize various types of polarization phenomena. These phenomena can be used to infer useful geological information as well. For example, the "bump" in Fig. 10 at frequency f_2 is caused by polar molecules rotating in the applied electric field. Since oil is relatively non polar, then one would conclude that only the water was giving raise to this signal. This could be useful in finding missed oil behind casing. In addition, it is known that shales conduct Na^+ ions but physically bind Cl^- ions, which is one of the primary reasons why spontaneous potentials exist in formation (John T. Dewan, op. cit., p. 38). In addition, it is known that Na^+ and Cl^- in general have different mobilities in a variety of different geological circumstances. Therefore, it is reasonable to expect that numerous interpretation schemes will evolve to determine the influence of different mobilities on polarization data which will allow inference of the lithology of the adjacent formation. In particular, therefore, the invention may be intentionally used in such a manner to emphasize the appearance of electrochemical effects, or polarization effects, which may be interpreted to yield certain geological parameters of interest related to the types of fluids present and the lithology of the formation.

For the sake of simplicity to this point, the power amplifier 18 has been described as delivering only sinusoidal A.C. current to the formation. However, the signal generator 14 is capable of many types of complicated waveforms which can be amplified by the power amplifier 18. By way of example, power amplifier 18 may be a D.C. coupled amplifier. Namely, the signal generator can put out an A.C. voltage which is offset by some D.C. bias voltage which therefore causes A.C. current to be conducted between electrode A and B but which has a D.C. offset current which may be larger in magnitude than the 0-peak magnitude of the A.C. current or the signal generator can put out voltage steps, triangle waves and other transient waveforms. To generalize the measurement concepts here, to this point, V_3, ΔI, V_o and I have been defined for simplicity as the O-peak values of assumed symmetric A.C. quantities. However, the various quantities may not be simply sinusoidal in nature, and therefore it is appropriate to consider a general time representation for the above quantities since O-peak values are not always useful for general waveforms.

If a time varying current I(t) passes through meter 42 in Fig. 1, then the voltage of the casing near electrode A with respect to an infinitely distant reference electrode becomes a time varying voltage $V_o(t)$ which produces a differential voltage signal $V_3(t)$ from amplifiers 26, 28, and 30 respectively due to the time varying loss of current $\Delta I(t)$ between electrodes C, D, and E into formation. Fig. 32 shows the measurement of $V_3(t)$ by an oscilloscope 88 labeled as OS1 in the drawing. The oscilloscope receives it's trigger from cable 36 from the sync output of the signal generator. The measurement of I(t) is accomplished by measuring the differential voltage across resistor R1 with oscilloscope 90 which is labeled as OS2 in Fig. 32. The output of the power amplifier PA is identified as $V_{PA}(t)$. The quantity of $V_o(t)$ is measured as shown in Fig. 33. This figure is similar to Fig. 3 except $V_o(t)$ is measured with the oscilloscope 88 which receives it's trigger from cable 36 attached to the sync output of the signal generator. Here too, R1 allows measurement of I(t) with oscilloscope 90.

Another way to measure such waveforms is by using a signal averager in place of the oscilloscope OS1. Suitable signal averagers are manufactured by many firms including EG&G Princeton Applied Research Corporation (op. cit.). Fig. 34 is nearly identical to Fig. 32 except the signal averager 92 marked as SA in Fig. 34 replaces the oscilloscope 88 in Fig. 32. And furthermore, Fig. 35 is identical to Fig. 33 except here the signal averager 92 marked as SA in Fig. 35 replaces the oscilloscope 38 in Fig. 33. Signal averagers are used to enhance the signal-to-noise ratio of repetitive waveforms which may have arbitrary shapes in time.

In addition, the signal generator 14 has been defined to include all manner of signal generators capable of providing the required voltage waveforms to measure the various parameters desired. Specifically, for the cases which follow, it is convenient to explicitly use a form of signal generator also known as an arbitrary waveform generator to perform said measurements. An example of such an instrument is the Model 175 Arbitrary Waveform Generator supplied by Wavetek, Corp. (9045 Balboa Avenue, San Diego, California 92138). Such an arbitrary waveform generator may also require a means of programming it, such as a computer with a suitable communications interface. However, the signal generator is to be viewed here as a voltage source which supplies periodic waveforms (including one-shot waveforms) which operates at frequencies from one millihertz to 20 kilohertz, and has arbitrary shapes of voltage vs. time which may be defined by the user of the signal generator.

Therefore, the invention has provided means to measure the arbitrary time response of $V_3(t)$, $\Delta I(t)$, $V_o(t)$, and $I(t)$. And now it is possible to discuss the response of $V_3(t)$ and $\Delta I(t)$ to applied $V_o(t)$ or applied $I(t)$ which may be asymmetric, or transient waveforms, or both. For example, a chosen $V_o(t)$ which is the sum of a small A.C. voltage and a larger D.C.

offset voltage may be applied to the formation, and then $V_3(t)$ and $\Delta I(t)$ can be determined. Or I(t) may be a current step, and then $V_3(t)$ and $\Delta I(t)$ could be determined. (The shape of the current may be controlled by varying the voltage supplied by the arbitrary waveform generator until the shape of the current through resistor R1 on oscilloscope OS2 looks appropriate.) Basically, polarization effects may be observed with such transient techniques. And furthermore, such effects can be either enhanced or minimized using such techniques as shown by the following examples.

Figs. 36 through 39 show one set of curves for one method of measurement. Here, the voltage from the arbitrary waveform generator is adjusted using instrumentation in Fig. 35 until the voltage $V_o(t)$ looks like that shown in Fig. 36. There is a sinusoidal variation in $V_o(t)$ on top of a larger D.C. offset labeled as V_o(offset) in Fig. 36. Fig. 37 shows the corresponding response of the total current I(t) conducted into the formation as measured with oscilloscope OS2 in Fig. 35. The signal averager 92 in Fig. 34 would then display the voltage $V_3(t)$ as shown in Fig. 38. The differential current $\Delta I(t)$ vs. time conducted into formation between electrodes C and E in Fig. 34 is shown in Fig. 39. In particular, both $V_3(t)$ in Fig. 38 and $\Delta I(t)$ in Fig. 39 show evidence of "rectification phenomena" associated with asymmetric ionic flow characteristic of the presence of clay materials as previously described. By taking data for various different intentionally set offset voltages V_o(offset), various types of polarization phenomena may be measured as previously described.

Figs. 40 through 43 show yet another method of measurement. Here, the voltage from the signal generator which is an arbitrary waveform generator is adjusted in Fig. 35 until the voltage output of the power amplifier, $V_{PA}(t)$, looks like the offset square wave as shown in Fig. 40. The current I(t) is monitored by observing the current through R1 with oscilloscope OS2. The actual casing potential near electrode A, $V_o(t)$, will therefore look approximately as shown in Fig. 41. The differential voltage $V_3(t)$ consequently looks approximately as shown in Fig. 42. And the differential current $\Delta I(t)$ conducted into formation is shown in Fig. 43. The waveforms in Fig. 42 and 43 look like waveforms associated with a "leaky capacitor" occasionally seen in electronics laboratories, and this is for good reason.

The casing problem here resembles a "leaky capacitor" for detailed analysis. The casing itself resembles the inner electrode of a cylindrical capacitor, and the earth at infinity can be identified with the outer electrode of the hypothetical cylindrical capacitor. The material in this conceptual capacitor has a resistivity, and much of the preferred embodiment of the invention is directed at measuring that quantity. However, the rock contains fluids, primarily salt water and oil, and these fluids are dielectrics. The presence of the electric field on the outer portion of the casing which points radially away from the casing tends to polarize any liquids present. It is generally known that the dielectric constant for water is much greater than the dielectric constant for oil at low frequencies, because water is a polar molecule which orients in the applied electric field whereas oil is not usually a highly polar molecule. The relative dielectric constant of oil is typically around the value of 2 compared to free space, and the relative dielectric constant of water is approximately 80 times that of free space (please see Applied Geophysics, W.M. Telford, et al., Cambridge University Press, Cambridge, New York 1981, table 5.7, p. 456). Of course the dielectric constant of the formation adjacent to the casing is dependent upon other variables such as the pore structure, pressure, temperature, and other parameters, but all other variables being constant, the dielectric constant of a formation containing water is much greater than an equivalent formation containing petroleum.

The physical processes in the hypothetical leaky capacitor are perhaps best explained in terms of Figs. 40 thru 43. As already cited, good background material concerning polarization effects which produce surface charges is given in Sections 30-3, 30-4, and 30-5 in David Halliday, et al., op. cit. When $V_{PA}(t)$ is applied to the casing at time t_1, then the local casing potential $V_o(t)$ eventually raises to the voltage V_{01} shown in Fig. 41 by the time t_2 is reached, and any oil and water present is polarized by the electric field applied to the formation adjacent to the energized casing.

The formation also simultaneously conducts current via the usual resistivity mechanisms already described. Therefore, if no polarization phenomena were present, then the capacitor would conduct current ΔI_1 as defined in Fig. 43. But the extra current required to polarize the molecules present results in an "overshoot" to ΔI_2 in Fig. 43 at time t_1. By the time t_2 is reached, when the voltage $V_{PA}(t)$ applied to the formation is discontinuously set to zero, there still exists charge on the outside of the casing due to the polarized molecules present which needs to be discharged through the casing and the adjacent resistive formation. (The surface charge is conducted to "ground" by the usual conduction processes through the geological formation.) Therefore, even through the driving voltage, $V_{PA}(t)$ is zero at time t_2, the discharging surface charge creates a momentary current flow, which flows off the casing and into the formation. Therefore, the resulting differential voltage $V_3(t)$ does not instantaneously go to zero, but instead behaves in general as shown between t_2 and t_3 in Fig. 42. There also exists a momentary flowing current $\Delta I(t)$ as shown between times t_2 and t_3 in Fig. 43. The rounded shapes of the waveforms in Figs. 42 and 43 are due to the skin depth effects of the casing which electronically behave like low-pass filters to current flow. This information may be used to obtain the average dielectric constant of the region of the geological formation adjacent to the borehole casing using the following methods of analysis.

For this analysis, it is necessary to determine the charge per unit length on the outside of the casing after the casing achieves a certain voltage level. It is perhaps easiest to calculate this quantity during the application of the voltage step to the casing between time t_1 to t_2. With reference to Fig. 43, before application of the voltage step, the casing is assumed to be discharged (the separation in time from t_2 to t_3 is chosen to allow discharge of the casing). And the time difference between t_1 and t_2 is chosen to allow a steady state to be achieved after the voltage step is applied. The effects of the resistivity allows conduction of the steady state current ΔI_1 into formation. However, during the application of the voltage step, there is an overshoot in the current from the value of ΔI_1 to a peak value of ΔI_2 shown in Fig. 43 which subsequently decreases back to the steady state "resistivity" component of the current ΔI_1. This "overshoot" in the current physically results in charging up the exterior of the casing to the voltage level of V_{01} defined in Fig. 41. Therefore, the charge per unit length on the outside of the casing between electrodes C and E is given by the following:

$$Q = \int_{t_1}^{t_2} \{ I(t) - I_1 \} \, dt / (2 L) \qquad \text{Eq. 27}$$

Since the voltage to which the capacitor charges is also known from Fig. 41 (the quantity V_{01} in Fig. 41), then the capacitance per unit length C can be computed from the following definition of the capacitance:

$$C = Q / V_{01} \qquad \text{Eq. 28}$$

The finite length of casing between electrodes C and E can be approximated mathematically for convenience as an ellipsoid of revolution where the length is 2L and the diameter is d. Then the capacitance of such an ellipsoid is given by the following equation where κ is the relative dielectric constant of the medium, and ϵ_o is the dielectric constant of free space (M.K.S. units). (Please see G.T. Tagg, p. 94, <u>op. cit.</u> for the basic equation in C.G.S. units, and to <u>Classical Electrodynamics</u> by John David Jackson, John Wiley & Sons, Inc., New York, Fifth Printing, 1966, p. 619 for conversion of C.G.S. units to M.K.S. units.)

$$C = 4 \pi \kappa \epsilon_o L / \mathrm{Ln} (4 L / d) \qquad \text{Eq. 29}$$

Therefore, the relative dielectric constant κ of the medium adjacent to the casing is given as follows, where the experimentally measured variables of Q, and V_{01} are explicitly shown for convenience:

$$\kappa = Q \ln (4 L / d) / (4 \pi \epsilon_o L V_{01}) \quad \text{Eq. 30}$$

The relative dielectric constant κ of the geological formation adjacent to the casing is useful for a variety of reasons. The relative dielectric constant can be approximated to first order by the sum of the volumes of materials present v_i times their individual relative dielectric constant κ_i which is in turn divided by the total volume of the sample as follows:

$$\kappa = \sum_i (\kappa_i v_i) / \sum_i v_i \quad \text{Eq. 31}$$

This approximation neglects important fluid boundary effects, and other corrections, but is reasonable as a starting point for discussion. However, the dielectric constant of water is much larger than either the dielectric constant of the oil or rock present, and therefore, if at least some water is present, then the dielectric constant measured is due primarily to the water. Under these circumstances, the relative dielectric constant is given by the following:

$$\alpha \simeq \gamma \kappa_w S_w \Phi \quad \text{Eq. 32}$$

Here, γ is the tool calibration constant, κ_w is the relative dielectric constant of water, S_w is the saturation factor of water present, and Φ is the porosity of the formation. The porosity Φ is the amount of "hole" space in the rock, and S_w is the fraction of hole space filled with water. (For additional information on terminology and an explanation of how oil in place is measured, please refer to John T. Dewan, op. cit.)

From Eq. 32, if the porosity is known, then the water saturation S_w is known. The porosity in general is known from original logs taken before the casing was set. Or the porosity can be reasonably measured with the current generation of through-casing tools using neutron tools, acoustic velocity tools, or density tools. If no gas is present, then the amount of oil in place (O.I.P.) is given as follows:

$$O.I.P. = (1 - S_w)\,\Phi \qquad \text{Eq. 33}$$

If gas is also present, the "O.I.P." gives the volume of oil and gas present. Such methods of analysis are generally discussed in John T. Dewan, ibid.

The above theory for the capacitance neglects important electrochemical phenomena which may have a large influence on the effective relative dielectric constants κ_i and on other parameters which may significantly enhance the size of the capacitance calculated from Eq. 29. The formula is included here to help explain how the invention works, and may not include all relevant numerical terms. The measured calibration factor γ for the tool as defined in Eq. 32 is used to adjust for such limitations of the theory.

In the above analysis, the "driving" element is the voltage $V_{PA}(t)$ delivered by the power amplifier. In fact, any type of "voltage drive" can be delivered by the power amplifier, and the data analyzed to determine resistivity and capacitance. Any type of "current drive" can also be provided by the power amplifier 18 and the data analyzed in principle to separate effects of resistivity and capacitance. For example, Fig. 44 shows a form of current drive where the output of the voltage from the power amplifier $V_{PA}(t)$ which is controlled by the signal generator which is an arbitrary waveform generator is adjusted until the current I(t) passed between electrode A and B looks like Fig. 44 and measurements performed. And similarly, the output of the power amplifier could be chosen as shown in Fig. 45. And again, the voltage output of the power amplifier could be chosen to look like Fig. 46 as desired by the operator. And lastly, another form of current drive is shown in Fig. 47 wherein the arbitrary waveform generator is used to generate a voltage output from the power amplifier $V_{PA}(t)$ such that the current passed between electrodes A and B looks like that shown in Fig. 47 and measurements performed. One technique may have a better sensitivity than another, but in principle, various different current or voltage waveforms applied to the casing result in differential current flow into the geological formation which may be measured with two or more pairs of voltage measurement electrodes to infer the resistivity of the adjacent formation, the capacitance of the casing adjacent to the formation, and hence the dielectric constant of the adjacent fluids. Any frequency sweep, voltage ramp, or triangle waveform can also be used. Different types of voltage and current drives between electrodes are used for similar analysis in the chemistry field, and will work here to various degrees of success. Please refer to Chapter 5 entitled "Techniques of Measurement" in Ilana Fried, op. cit. and Section 1.6 entitled "Electroanalytical Techniques" in Derek Pletcher, op. cit.

Fig. 48 shows another application for the Thru Casing Resistivity Tool. A drill stem 94 used to turn a drilling bit 96 has drilled an open-hole 98 through the geological formation 8 and through oil bearing formation 10. As is usually the case, drilling fluids 100 fill the open borehole. And as is typically the case in porous regions such as in oil bearing formations, a "cake" 102 forms on the wall of the open borehole due to the invasion of fluids into the formation. The "invaded zone" of the formation is labeled as 104. The radius of the drill string is r_4, the thickness of the drill string pipe is τ_1, the radius of the open hole at any given vertical position is r_5, and the radius of the invasion zone at any vertical position is r_6. Two individual Thru Casing Resistivity Tool apparatus are lowered into the inside of the drill stem while the drilling bit is stopped which are labeled Tool I and Tool II in Fig. 48. Tool I has electrodes A, C, D, E, and F which are defined functionally in Fig. 1. Electrodes C and D, and D and E are separated by the distance L_9. The distance L_{10} separates electrodes A and C and electrodes E and F. Measurements are performed with the apparatus as defined conceptually in Figs. 1 and 3 and in Figs. 34 and 35. In addition, another independent tool, labeled Tool II, is mechanically connected to Tool I and has electrodes A'', C'', D'', E'', and F''. The distances L_{11}, L_{12}, and L_{13} are defined in Fig. 48.

Because Tool I and Tool II have different separations of voltage measurement electrodes (L_9 and L_{11} respectively), then their depths of investigation of the formation will be different. Therefore, if the resistivity of the drilling fluids are known, and L_9 and L_{11} are chosen suitably, then the apparatus can measure the resistivity of the far zone and that of the invaded zone using the usual analysis techniques for such measurements which are routinely used in the measurement of open hole resistivity logs. This type of tool is superior to other "measurement while drilling" or measurement while drilling bit stopped" techniques because this tool requires no downhole maintenance. If something goes wrong with the tool, then the tool may be removed from the drill stem and another inserted for measurement, and the drilling bit need not be removed from the hole which is a time consuming and therefore expensive process. Any number of tools resembling Tool I and Tool II can be used inside the drill stem for different purposes, including just one tool to three or more such tools. The resistivity of the drilling mud may also be independently measured at the surface of the earth which will allow corrections to the acquired data thereby allowing greater accuracy in the calculated resistivity of the geological formation.

In addition, the size of the measured signal due to the differential current conducted into formation is proportional to the resistivity of the drill stem, and inversely proportional to it's thickness, and it's diameter. Therefore, portions of the drill stem may be intentionally fabricated from relatively high resistivity materials to enhance the signal for measurement purposes. Portions of the drill stem may be heat treated differently thereby causing differences in the resistivity along its length for example. Different materials can be welded together causing changes in the resistivity of the drill stem. The drill stem's geometry over specific portions of its length can be changed to enhance the differential voltage signal. Furthermore, such modifications of the drill stem can also be used to change the effective radius of penetration of the tool to help determine differences between the far region of the formation, the invaded zone, and borehole fluids.

In addition, magnetic fields on the inside of the casing can be used to adjust the magnetic permeability of the casing material. The skin depth of the casing is a function of the magnetic permeability as shown in Eq. 22. Therefore, a magnetic means located on the inside of borehole casing or a drill stem can be used to magnetically saturate the steel pipe, which therefore substantially changes the magnetic permeability which in turn changes the effective skin depth. Such effects can also be used to adjust the radius of investigation of the invention in a drill stem, or inside any iron casing which is inside any typical cased well.

In addition, another variation of the invention is a true measurement-while-drilling apparatus. A permanently located downhole tool with electrode configurations shown in Fig. 48 can obtain its power from flowing mud in the hole. Then multi-electrode measurements can be performed and the results sent to the surface by encoded mud pressure pulses as is typical in the industry.

And in addition, measurements of the electronic properties of formations through casing may be performed while simultaneously subjecting the formation and the casing to an acoustic energy source. For example, resistivity measurements may be performed thru casing while conducting a current of one frequency through casing. If the acoustic source is energized at another frequency, then the differential current conducted into formation will be modulated at the sum and difference frequencies because the resistivity of the formation will be acoustically modulated. And since the elastic properties of cement and the surrounding geological formation are different, methods based on the acoustic modulation of formation resistivity may be used to determine the presence or absence of cement surrounding the casing. Similarly, measurements of electrochemical phenomena can be performed while simultaneously subjecting the formation to an acoustic source. Convenient acoustic sources inside casing are piezoelectric crystals and any type acoustic source may be used outside the casing on the surface of the earth or in another borehole.

And finally, yet another variation of the tool can be used to monitor water quality in fresh water wells. In many cases, fresh water wells contain pipes which carry water to the surface for consumption. Monitoring such wells for contamination is now a major problem in many areas of the nation. The invention may be used to monitor resistivity and polarization phenomena through well pipes to monitor water quality.

While the above description contains many specificities, these should not be construed as limitations on the scope of the invention, but rather as exemplification of preferred embodiments thereto. As has been briefly described, there are many possible variations. And despite the fact that much specific and detailed theory has been presented which explain the microscopic physical processes which pertain to the invention, and even if such theory improves in time with later physical investigations and measurements, none-the-less, independent of the detailed physical processes at work, the invention provides a means to measure the resistivity and the dielectric constant of the adjacent geological formation through borehole casing. Accordingly, the scope of the invention should be determined not only by the embodiments illustrated, but by the appended claims and their legai equivalents.

WHAT IS CLAIMED IS:

1. A method for measuring electrochemical phenomena of formations adjacent to a cased borehole comprising the steps of:

causing a current to enter the casing in the proximity of the specific portion of the formation to be tested;

selectively receiving at least a portion of the current at a point sufficiently remote from the current entry point to insure that a majority of the current introduced at the current entry point enters the formation along the length of the borehole casing;

detecting the voltage level at a plurality of at least three spaced apart voltage measuring points along the casing, said disposition of electrodes defining a specific portion of the casing which is adjacent to the specific portion of the formation to be tested; and

measuring the differential voltages between a plurality of discrete pairs of said spaced apart voltage measuring points.

2. A method as recited in Claim 1 wherein said voltage measuring points are horizontally spaced apart within the casing.

3. A method as recited in Claim 1 wherein the voltage measuring points are vertically spaced apart within the casing.

4. A method as recited in Claim 1 wherein the electrochemical phenomena measured includes formation polarization phenomena and wherein the current introduced to the casing is an alternating current having a frequency in the range of .01 to 5.0 Hz.

5. A method as recited in Claim 1 wherein the electrochemical phenomena measured includes formation resistivity and wherein the current introduced to the casing is an alternating current having a frequency in the range of 0.1 to 20 Hz.

6. A method as recited in Claim 1 wherein the monitored formation is a cement layer adjacent to the casing.

7. A method as recited in Claim 1 wherein the monitored formation is a reservoir of water.

8. A method as recited in Claim 2 adapted to measure the permeability of the geological formation, the method further comprising the step of introducing a fluid into the formation.

9. A method as recited in Claim 1 further comprising the steps of:

selecting a calibration mode and causing a current to flow between a first calibration point disposed on a first side of the voltage measuring points, and a second calibration point disposed on the opposite side of the voltage measuring points; and

proportionally amplifying the voltage differential between a first one of said discrete voltage measuring point pairs to substantially equal the voltage differential of a second one of said discrete voltage measuring point pairs during said calibration mode.

10. A method for measuring electrochemical phenomena of formations adjacent to a cased borehole comprising the steps of:

causing a current to enter the casing in the proximity of the formation to be tested;

selectively receiving at least a portion of the current at a point in contact with the earth's surface and spaced apart from the casing;

detecting the voltage level at a plurality of at least three spaced apart voltage measuring points along the casing; and

measuring the differential voltages between a plurality of discrete pairs of said spaced apart voltage measuring points.

11. A method for monitoring the integrity of a cement layer adjacent to a metal pipe which is located within a drill hole in a geological formation comprising the steps of:

causing a current to enter the pipe in the proximity of the portion of the cement layer to be tested;

selectively receiving at least a portion of the current at a point sufficiently remote from the current entry point to insure that a majority of the current introduced at the current entry point enters the geological formation;

detecting the voltage level at a plurality of at least three spaced apart voltage measuring points along the casing;

measuring the differential voltages between a plurality of discrete pairs of said spaced apart voltage measuring points; and

interpreting the measured differential voltages to predict cement integrity.

12. A method as recited in Claim 11 wherein said spaced apart voltage measuring points are horizontally spaced apart.

13. An apparatus for measuring electrochemical phenomena of predetermined specific formations adjacent to a cased borehole surrounded by formations comprising:

introduction means for selectively causing a measuring current to enter the casing at a point in the proximity of the specific formation of interest;

receiving means for receiving at least a portion of the current at a point sufficiently remote from the current entry point to insure that a majority of the current introduced by said current introduction means enters the formation from the casing;

voltage measuring means for detecting the voltage level at a multiplicity of at least three spaced apart voltage measuring points along the casing, said disposition of electrodes defining the specific section of the casing which is adjacent to the specific portion of the formation to be measured; and

differential means for simultaneously measuring the differential voltages between a plurality of discrete pairs of said voltage measuring points to provide information about the specific formation of interest.

14. An apparatus as recited in Claim 13 wherein said voltage measuring points are vertically spaced apart within the casing.

15. An apparatus as recited in Claim 13 wherein said voltage measuring points are horizontally spaced apart within the casing.

16. An apparatus as recited in Claim 13 wherein said receiving means includes an earth contacting electrode spaced apart from the casing and in electrical contact with the earth.

17. An apparatus as recited in Claim 13 wherein said receiving means includes a receiving electrode in electrical contact with the casing.

18. An apparatus as recited in Claim 13 wherein said apparatus has a measurement mode and a calibration mode, the apparatus further comprising:

a calibration means for calibrating the differential voltages between said plurality of discrete pairs of voltage measuring points; and

means for alternately selecting said measurement mode or said calibration mode.

19. An apparatus as recited in Claim 18 wherein said calibration means includes a first calibrating electrode in electrical contact with said casing on a first side of the voltage measuring points and a second calibrating electrode disposed on the opposite side of said voltage measuring points, said means also providing means to conduct current between said first and second calibrating electrodes.

20. An apparatus as recited in Claim 19 wherein said first calibrating electrode is adapted to introduce current into the casing when the apparatus is in the measurement mode.

21. An apparatus as recited in Claim 19 wherein the calibration means further includes a balancing means for receiving and comparing the differential voltages obtained between discrete pairs of voltage measuring points, the balancing means including:

a gain controller for amplifying a first differential voltage reflecting the voltage difference of a first pair of voltage measuring points by an adjustable calibrating gain, whereby the calibrating gain is chosen when the apparatus is in the calibration mode, and

comparison means for comparing the voltage difference between the amplified first differential voltage and a second differential voltage reflecting the differential voltage of a second pair of voltage measuring points, whereby the comparison means provides a measurement signal that is indicative of the relative current leak from the casing into the formation between the first and second pairs of voltage measuring points when the apparatus is in the measurement mode.

22. An apparatus as recited in Claim 21 wherein the calibrating gain is chosen to cause the amplified first differential voltage to substantially equal the second differential voltage when the apparatus is in the calibration mode.

23. An apparatus as recited in Claim 22 wherein the measurement signal is produced by differential means which measures the differential voltage between the amplified first differential voltage and the second differential voltage.

24. An apparatus as recited in Claim 23 wherein the differential means includes a plurality of first level differential amplifiers, each said differential amplifier producing a signal that reflects the voltage difference between a discrete pair of the voltage measuring points.

25. An apparatus as recited in Claim 24 wherein the comparison means includes a second level differential amplifier that produces the measurement signal.

26. An apparatus as recited in Claim 13 wherein the measuring current is an alternating current.

27. An apparatus as recited in Claim 26 wherein the measuring current has a frequency in the range of 0.1 to 20 Hz.

28. An apparatus as recited in Claim 27 wherein the measuring current is in the range of .1 to 30 amps, zero to peak.

29. An apparatus as recited in Claim 26 wherein the measuring current has a frequency in the range of .01 to 5.0 Hz.

30. An apparatus as recited in Claim 13 wherein said introducing means includes a first current conducting electrode disposed within and engaged in electrical contact with the casing for introducing the measuring current to the casing.

31. An apparatus as recited in Claim 13 wherein said introducing means includes a plurality of current conducting electrodes disposed within and engaged in electrical contact with the casing for introducing the measuring current onto the casing.

32. An apparatus as recited in Claim 13 wherein said voltage measuring means includes a multiplicity of at least three vertically spaced apart rows of voltage measuring points, each said row including a plurality of at least three horizontally spaced apart voltage measuring points.

33. A method for measuring electrochemical phenomena of a formation while drilling a borehole through the

formation using a drill having a drill bit and a metal drill stem extending uphole from the bit, the method comprising the steps of:

drilling through the formation;

applying a measurement current to the drill stem;

selectively receiving at least a portion of the current at a point in electrical contact with the earth that is spaced apart from the borehole;

detecting the voltage level at a plurality of at least three spaced apart voltage measuring points along the drill stem;

measuring the differential voltages between a plurality of discrete pairs of the spaced apart voltage measuring points; and

interpreting the measured differential voltages to predict formation characteristics.

34. A method as recited in Claim 33 further comprising the step of applying a magnetic field to the drill stem during the current applying step.

35. An apparatus for measuring the electronic properties of formations penetrated by a borehole from within a metallic pipe which is positioned within said borehole, said apparatus comprising:

means for generating a time varying electric field on the exterior of the metallic pipe whereby said electric field has at least a component which is perpendicular to the metallic pipe thereby causing a total time varying current to be conducted from the metallic pipe into the formation which is in electrical contact with the metallic pipe; and

means for simultaneously measuring the time varying differential current conducted into the formation from a predetermined portion of the metallic pipe adjacent to the specific portion of the formation to be measured which provides information useful for measuring the electronic properties of formations.

36. The apparatus as recited in Claim 35 wherein said means for generating a time varying electric field on the exterior of the metallic pipe is comprised of current conducting means which conducts time varying current from a current conducting electrode which is in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured to a current conducting electrode which is in electrical contact with the surface of the earth.

37. The apparatus as recited in Claim 36 wherein the current conducting means conducts sinusoidally varying current in time from the current conducting electrode which is in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured to the current conducting electrode which is in electrical contact with the surface of the earth.

38. The apparatus as recited in Claim 36 wherein the current conducting means conducts transient current in time from the current conducting electrode which is in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured to the current conducting electrode which is in electrical contact with the surface of the earth.

39. The apparatus as recited in Claim 35 wherein said means for generating a time varying electric field on the exterior of the metallic pipe is provided by a time varying voltage generating means whereby one output of the time varying voltage generating means is connected to a current conducting electrode which is

in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured and the other output of the time varying voltage generating means is connected to a current conducting electrode which is in electrical contact with the surface of the earth.

40. The apparatus as recited in Claim 39 wherein said voltage generating means provides a sinusoidally varying voltage in time.

41. The apparatus as recited in Claim 39 wherein said voltage generating means provides a transient voltage in time.

42. The apparatus as recited in Claim 35 wherein the means for measuring the time varying differential current conducted into the formation from the predetermined portion of the metallic pipe is comprised of at least two pairs of voltage measurement electrodes which are in electrical contact with the interior of the metallic pipe, whereby the first pair of said voltage measurement electrodes provides the first time varying voltage output and said second pair of said voltage measurement electrodes provides the second time varying voltage output and whereby voltage difference means are also provided which subtracts said first and second time varying voltage outputs thereby providing a third time varying voltage output which is responsive to the time varying differential current conducted into formation from the predetermined portion of the metallic pipe which is geometrically defined by the disposition of said pairs of voltage measurement electrodes.

43. The apparatus as recited in Claim 35 wherein said metallic pipe is comprised of a drill stem which is attached to a drilling bit which is used to drill holes in geological formations.

44. The apparatus as recited in Claim 43 wherein the formation of interest to be measured is comprised of drilling fluids inside the drill hole and the adjacent geological formation.

45. The apparatus as recited in Claim 35 wherein the metallic pipe is comprised of borehole casing and the formation to be measured includes any cement present surrounding said borehole casing and the adjacent geological formation.

46. The apparatus as recited in Claim 36 wherein said current conducting electrode which is in electrical contact with the surface of the earth is an electrode which is attached to the borehole casing near the surface of the earth provided that the distance between said electrode and the electrode which is in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured is sufficiently large such that a majority of the current conducted between said electrodes passes through the geological formation surrounding the metallic pipe.

47. The apparatus as recited in Claim 36 wherein said current conducting electrode which is in electrical contact with the surface of the earth is an electrode which is attached to the borehole casing at some depth from the surface of the earth provided that the distance between said electrode and the current conducting electrode which is in electrical contact

with the interior of the metallic pipe in the vicinity of the formation to be measured is sufficiently large such that a majority of the current conducted between said electrodes passes through the geological formation surrounding the metallic pipe.

48. The apparatus as recited in Claim 35 wherein magnetic means are also provided which simultaneously applies a magnetic field to the formation to be measured and the metallic pipe adjacent to said formation.

49. The apparatus for measuring the electronic properties of formations as recited in Claim 35 wherein acoustic means are provided which simultaneously applies acoustic energy to the formation to be measured and to the adjacent metallic pipe.

50. The apparatus for measuring the electronic properties of formations as recited in Claim 35 wherein said apparatus is adapted to move inside said metallic pipe while simultaneously measuring said time varying differential current conducted into the formation.

51. An apparatus for measuring the electronic properties of formations adjacent to cased boreholes comprising:

means for generating and applying a time varying voltage between a current conducting electrode which is in electrical contact with the interior of the borehole casing in the vicinity of the formation to be measured and an electrode which is in electrical contact with the surface of the earth thereby causing a total time varying current to be conducted between the borehole casing and the electrode which is in electrical contact with the surface of the earth; and

means for measuring the time varying differential current conducted into formation from a predetermined section of the casing adjacent to the specific portion of the formation to be measured which provides information useful for measuring the electronic properties of formations.

52. The apparatus as recited in Claim 51 wherein the means for measuring the time varying differential current conducted into formation from a predetermined section of the borehole casing is comprised of at least two pairs of voltage measurement electrodes which are in electrical contact with the interior of the casing, whereby the first pair of said voltage measurement electrodes provides the first time varying voltage output and the second pair of said voltage measurement electrodes provides the second time varying voltage output and whereby voltage difference means are also provided which subtract said first and second voltage outputs thereby providing a third time varying voltage output which is responsive to the time varying differential current conducted into formation from the predetermined section of the casing which is geometrically defined by the disposition of said pairs of voltage measurement electrodes.

53. The apparatus as recited in Claim 52 wherein additional means are provided to measure the electrical resistance between each electrode of each pair of electrodes which are in electrical contact with the interior of the borehole casing thereby providing apparatus calibration means which thereby provides sufficient information to quantitatively measure the differential current conducted into

formation from the predetermined section of the borehole casing adjacent to the specific portion of the formation to be measured.

54. The apparatus as recited in Claim 53 wherein said pairs of voltage measurement electrodes are disposed vertically in the borehole and which are on a first vertical side of the current conducting electrode which is in electrical contact with the interior of the borehole casing.

55. The apparatus as recited in Claim 54 wherein each electrode of the voltage measuring electrode pairs are separated vertically by approximately equal distances.

56. The apparatus as recited in Claim 54 wherein the means of generating and applying the time varying voltage between the current conducting electrode which is in electrical contact with the interior of the borehole casing and the current conducting electrode which is in electrical contact with the surface of the earth is comprised of means which applies a sinusoidal voltage of a given magnitude and frequency between said electrodes, whereby the time varying differential current conducted into the formation from the predetermined section of the casing adjacent to the specific portion of the formation to be measured may be repeatedly measured for different magnitudes of applied voltages and different frequencies, thereby providing a means of measuring the electronic properties of formations adjacent to cased boreholes including the resistivity of the formation, the presence or absence of cement, the measurement of polarization phenomena and electrochemical phenomena.

57. The apparatus as recited in Claim 54 wherein the means for generating and applying a time varying voltage between the current conducting electrode which is in electrical contact with the interior of the borehole casing and the electrode which is in electrical contact with the surface of the earth is comprised of means which provides a transient voltage in time between said electrodes, whereby the time varying differential current conducted into the formation from the predetermined section of the casing adjacent to the specific portion of the formation to be measured may be repeatedly measured for different transient voltage waveforms, thereby providing a means of measuring the electronic properties of formations adjacent to cased boreholes including the resistivity of the formation, the presence or absence of cement, the measurement of polarization phenomena and electrochemical phenomena.

58. The apparatus as recited in Claim 53 wherein said pairs of voltage measurement electrodes are disposed azimuthally around the circumference of the casing at a given vertical location whereby the distance of separation of said electrodes is small compared to the circumference of the casing.

59. The apparatus as recited in Claim 58 wherein each electrode of the voltage measuring electrode pairs are separated by approximately equal distances.

60. The apparatus as recited in Claim 58 wherein the means for generating and applying a time varying voltage between the current conducting electrode which is in electrical contact with the interior of the borehole casing and the current conducting electrode which is in electrical contact with the surface of the

earth is comprised of means which provides a sinusoidal voltage of a given magnitude and frequency between said electrodes, whereby the time varying differential current conducted into formation from the predetermined section of the casing adjacent to the specific portion of the formation to be measured may be repeatedly measured for different magnitudes of applied voltages and different frequencies, thereby providing a means for measuring the electronic properties of formations adjacent to cased boreholes including the resistivity of the formation, the presence or absence of cement, the measurement of polarization phenomena and electrochemical phenomena.

61. The apparatus as recited in Claim 58 wherein the means for generating and applying a time varying voltage between the current conducting electrode which is in electrical contact with the interior of the borehole casing and the current conducting electrode which is in electrical contact with the surface of the earth is comprised of means which provides a transient voltage in time between said electrodes, whereby the time varying differential current conducted into the formation from the predetermined section of the casing adjacent to the specific portion of the formation to be measured may be repeatedly measured for different transient voltage waveforms, thereby providing a means for measuring the electronic properties of formations adjacent to cased boreholes including the resistivity of the formation, the presence or absence of cement, the measurement of polarization phenomena and electrochemical phenomena.

62. The apparatus as recited in Claim 51 wherein the current conducting electrode which is in electrical

contact with the interior of the borehole casing is in physical contact with the casing.

63. The apparatus as recited in Claim 51 wherein the current conducting electrode which is in electrical contact with the interior of the borehole casing makes electrical contact with said casing through electrically conductive fluid within said borehole casing.

64. The apparatus as recited in Claim 52 wherein the two pairs of voltage measurement electrodes which are in electrical contact with the interior of the borehole casing are in physical contact with the interior of the casing.

65. The apparatus as recited in Claim 52 wherein the two pairs of voltage measurement electrodes which are in electrical contact with the interior of the borehole casing make electrical contact with said casing through electrically conductive fluids within said borehole casing.

66. The apparatus as recited in Claim 53 wherein at least two pairs of voltage measurement electrodes are disposed vertically within the cased hole and at least two additional pairs of voltage measurement electrodes are disposed azimuthally around the circumference of the casing thereby providing a means to measure the dip and strike of the geological formation.

67. The apparatus as recited in Claim 53 wherein means are also provided which pumps fluids of known resistivities into the specific formations adjacent to the casing to be measured thereby providing means to measure the permeability of said formations and means

which are responsive to fractures within said formations.

68. The method for measuring the electronic properties of formations penetrated by a borehole from within a metallic pipe which is positioned within said borehole comprising the steps of:

applying a time varying electric field to the exterior of the metallic pipe whereby said electric field has at least a component which is perpendicular to the metallic pipe thereby causing a total time varying current to be conducted from the metallic pipe into the formation which is in electrical contact with the metallic pipe; and

simultaneously measuring the time varying differential current conducted into the formation from a predetermined portion of the metallic pipe adjacent to the specific portion of the formation to be measured which provides information useful for measuring the electronic properties of formations.

69. The method for measuring the electronic properties of formations as recited in Claim 68 wherein the method of applying a time varying electric field to the exterior of the metallic pipe is provided by passing current from a current conducting electrode which is in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured to a current conducting electrode which is in electrical contact with the surface of the earth.

70. The method for measuring the electronic properties of formations as recited in Claim 69 wherein the method of measuring the time varying differential current conducted into the formation from the predetermined portion of the metallic pipe

adjacent to the specific portion of the formation to be measured is performed by simultaneously measuring the time varying voltage outputs from at least two pairs of voltage measurement electrodes which are in electrical contact with the interior of the metallic pipe and which are located to one side of the current conducting electrode in electrical contact with the interior of the metallic pipe whereby the first time varying voltage output from the first pair of voltage measurement electrodes is simultaneously measured with the second time varying voltage output from the second pair of voltage measurement electrodes, and whereby these time varying voltage outputs are simultaneously subtracted thereby producing a third time varying voltage output which is also simultaneously measured which is responsive to said time varying differential current conducted into the formation to be measured.

71. The method for measuring the electronic properties of formations as recited in Claim 70 wherein measurements are additionally performed which determine the resistance between each voltage measuring electrode of each voltage measuring electrode pair thereby providing a method which allows quantitative computation of the time varying differential current conducted into formation.

72. The method of measuring the electronic properties of formations as recited in Claim 71 wherein the third time varying voltage output is measured while simultaneously passing a sinusoidal current from said current conducting electrode which is in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured to the current conducting electrode which is in electrical

contact with the surface of the earth, said sinusoidal current having a given magnitude and frequency.

73. The method of measuring the electronic properties of formations as recited in Claim 72 wherein measurements are repeatedly performed of said third time varying voltage outputs for different frequencies and magnitudes of sinusoidal currents conducted between said current conducting electrodes.

74. The method of measuring the electronic properties of formations penetrated by a borehole from within a metallic pipe as recited in Claim 73 wherein said metallic pipe is borehole casing which is surrounded by a formation comprised of any cement present and the adjacent geological formation whereby the amplitude and phase of the third time varying voltage output is measured for different frequencies and magnitudes of sinusoidal currents conducted between said current conducting electrodes which provides information responsive to the resistivity of the adjacent geological formation and to the presence or absence of cement surrounding the casing.

75. The method of measuring the electronic properties of formations through borehole casing as recited in Claim 74 wherein measurements are additionally performed which determine the local casing potential of the borehole casing in the vicinity of the formation to be measured while simultaneously passing said sinusoidal currents between said current conducting electrodes which provides sufficient information to calculate the resistivity of the adjacent formation which may be interpreted to provide the resistivity of the adjacent geological formation and indications of the presence or absence of cement.

76. The method of measuring the resistivity of formations as recited in Claim 75 wherein measurements are repeatedly performed of the amplitude and phase of the third time varying voltage for a given current conducted between said current conducting electrodes and at different frequencies substantially between .1 Hz and 5 Hz which provides sufficient information to calculate the resistivity of the adjacent geological formation and indications of the presence or absence of cement.

77. The method of measuring the resistivity of formations as recited in Claim 76 wherein the pairs of voltage measurement electrodes are placed substantially along the length of the interior of the borehole casing and said measurements at different frequencies are performed thereby providing information primarily used to infer the resistivity of the adjacent geological formation.

78. The method of measuring the resistivity of formations as recited in Claim 76 wherein the pairs of voltage measurement electrodes are placed in substantially different azimuthal positions around the interior circumference of the borehole casing thereby resulting in information primarily used to infer the integrity of the surrounding cement.

79. The method of measuring the electronic properties of formations penetrated by a borehole from within a metallic pipe as recited in Claim 73 wherein said metallic pipe is a borehole casing which is surrounding by a formation whereby the amplitude and phase of the third time varying voltage output is repeatedly measured for different frequencies and magnitudes of sinusoidal currents conducted between

said current conducting electrodes which provides information responsive to the electrochemical properties of formations which are also known as polarization properties of formations.

80. The method of measuring electrochemical properties of formations as recited in Claim 79 wherein measurements of the amplitude and phase of the third time varying voltage are repeatedly performed for a given current at different frequencies substantially between .01 Hz and 1 Hz, a frequency interval which emphasizes the appearance of polarization effects.

81. The method of measuring the electrochemical properties of formations as recited in Claim 80 wherein measurements are additionally performed which determine the local casing potential of the borehole casing in the vicinity of the formation to be measured while simultaneously conducting said sinusoidal currents between said current conducting electrodes thereby providing sufficient information to calculate the capacitance of the casing adjacent to the formation to be measured which provides a measure of the dielectric constant of the fluids within the adjacent formation.

82. The method of measuring the electronic properties of formations penetrated by a borehole from within a metallic pipe as recited in Claim 73 wherein said metallic pipe is a drill pipe attached to a drilling bit used to drill holes through geological formations which is surrounded by a formation comprised of any drilling mud present and the adjacent geological formation whereby the amplitude and phase of the third time varying voltage output is measured for different

frequencies and magnitudes of sinusoidal currents conducted between said current conducting electrodes which provides information responsive to the resistivity of the adjacent geological formation and to the resistivity of the drilling mud.

83. The method of measuring the resistivity of adjacent formations through a drill pipe as recited in Claim 82 wherein measurements are additionally performed which determine the local potential of the drill pipe in the vicinity of the formation to be measured while simultaneously passing said sinusoidal currents between said current conducting electrodes which provides sufficient information to calculate the resistivity of the adjacent formation.

84. The method of measuring the resistivity of adjacent formations through a drill pipe as recited in Claim 83 wherein measurements are also additionally performed of the resistivity of the drilling mud at the surface of the earth and whereby said measurements allow the computation of the resistivity of the adjacent geological formation.

85. The method of measuring the electronic properties of formations penetrated by a borehole from within a metallic pipe as recited in Claim 73 wherein said metallic pipe is a borehole casing which is surrounded by a formation comprised of any cement present and the adjacent geological formation whereby the amplitude and phase of the third time varying voltage output is measured for different frequencies and magnitudes of sinusoidal currents conducted between said current conducting electrodes while also simultaneously injecting known quantities of fluids into formation of known electrical resistivities which provides

information responsive to the permeability of the adjacent geological formation and to any fractures in said formation.

86. The method of measuring the permeability and fracturing of formations through borehole casing as recited in Claim 85 wherein measurements are additionally performed which determine the local casing potential of the borehole casing in the vicinity of the formation to be measured while simultaneously passing said sinusoidal current between said current conducting electrodes which provides sufficient information to quantitatively measure the permeability and fracturing of the adjacent geological formation.

87. The method for measuring the electronic properties of formations as recited in Claim 71 wherein the third time varying voltage output is measured while simultaneously passing transient currents from said current conducting electrode which is in electrical contact with the interior of the metallic pipe in the vicinity of the formation to be measured to the current conducting electrode which is in electrical contact with the surface of the earth.

88. The method for measuring the electronic properties of formations as recited in Claim 87 wherein the third time varying voltage output is measured while simultaneously passing transient current between said current conducting electrodes which is a square wave in time.

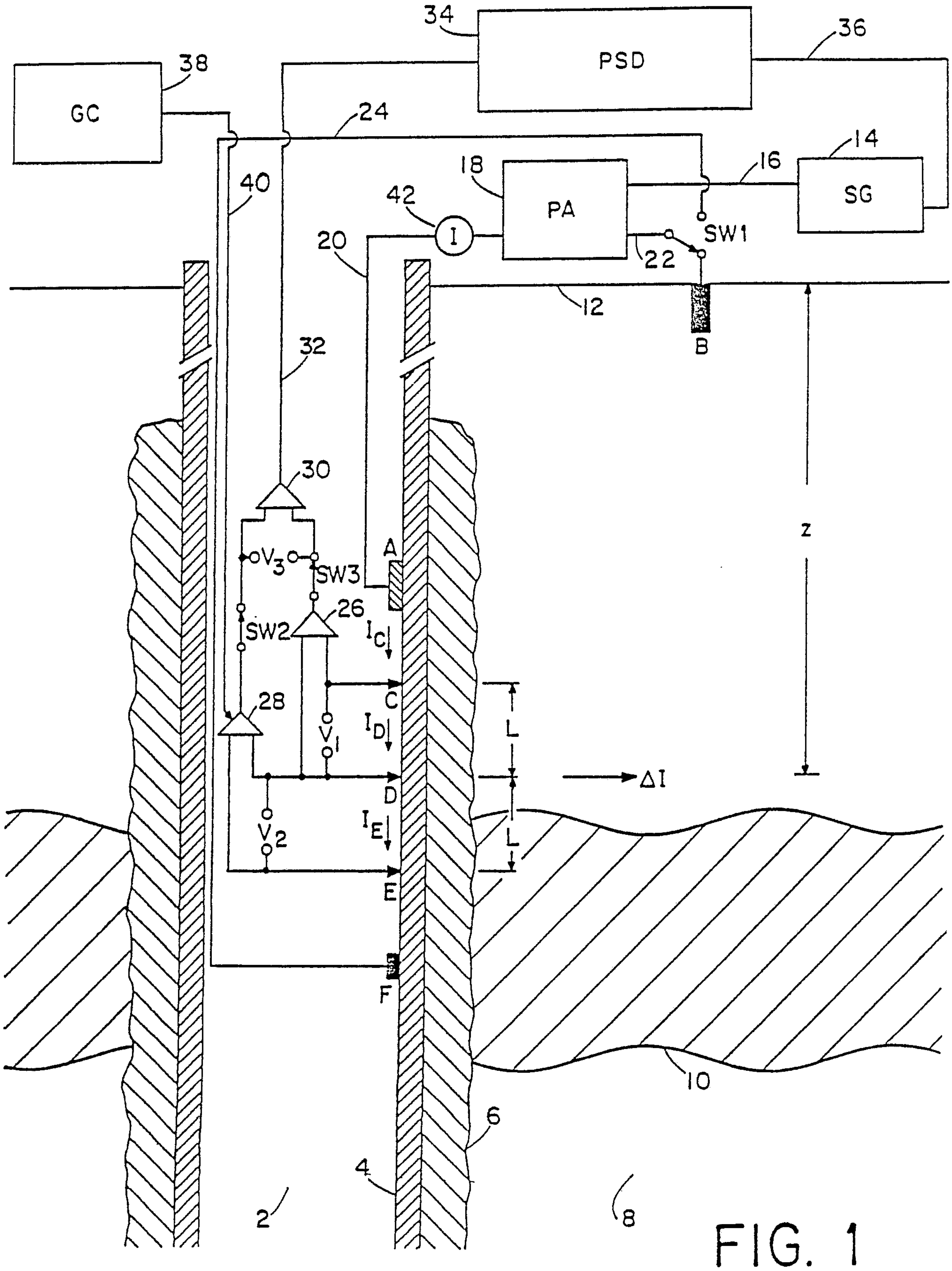
89. The method for measuring the electronic properties of formations penetrated by a borehole from within a metallic pipe as recited in Claim 88 wherein

said metallic pipe is a borehole casing which is surrounded by a formation comprised of any cement present and the adjacent geological formation whereby the third time varying voltage output is measured while simultaneously passing said square wave current in time between said current conducting electrodes which provides information responsive to the electrochemical properties of the adjacent formation.

90. The method of measuring the electronic properties of formations as recited in Claim 89 wherein said measurements of said third time varying voltage output are interpreted to measure the time dependent electrical charge on the exterior of the casing which therefore allows computation of the dielectric constants of the fluids in the adjacent geological formation.

91. The method for measuring the electronic properties of formations as recited in Claim 71 wherein a magnetic field is also simultaneously applied to the metallic pipe and the adjacent formation to be measured.

92. The method for measuring the electronic properties of formations as recited in Claim 71 wherein acoustic energy is simultaneously applied to the metallic pipe and the adjacent formation to be measured.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V3
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FIG. 1

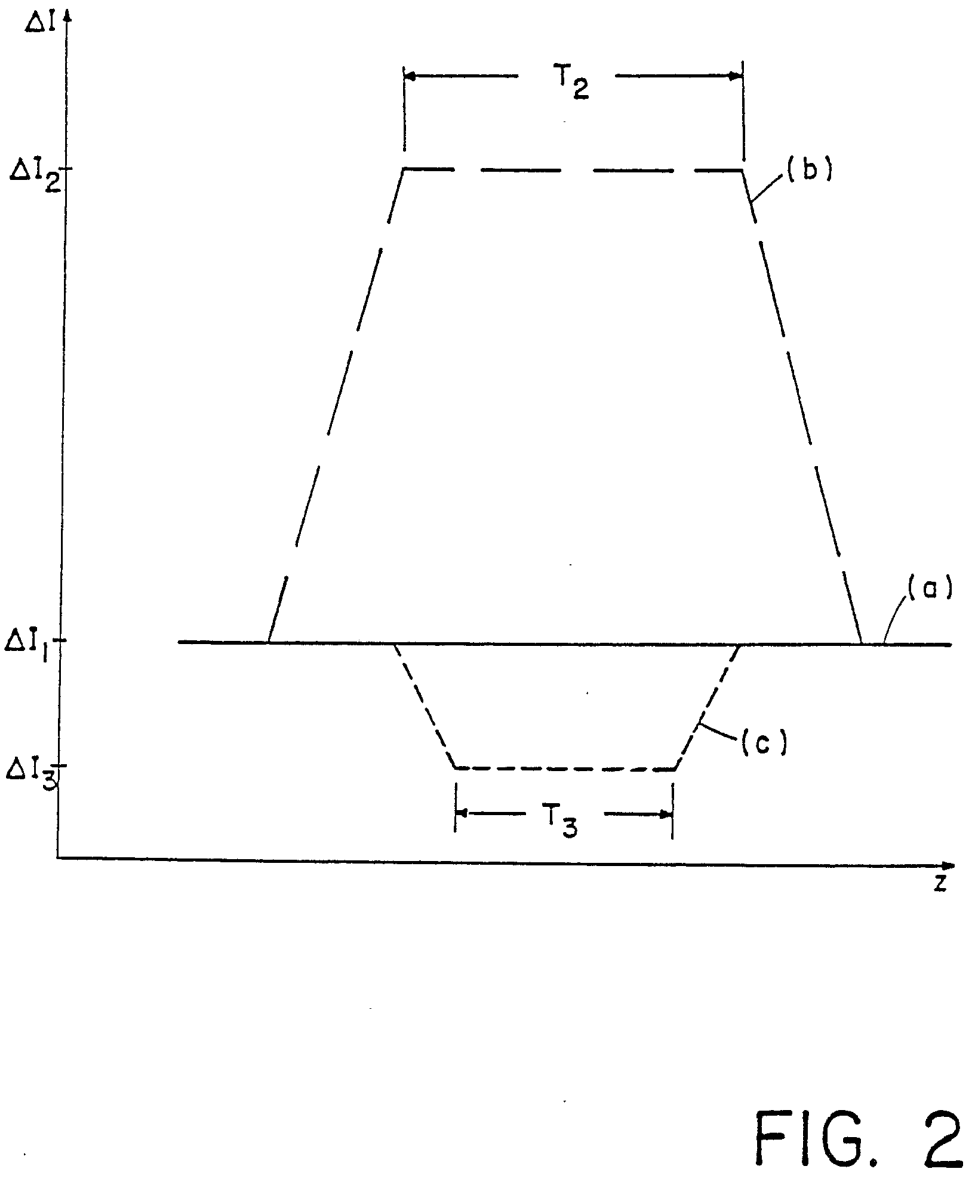
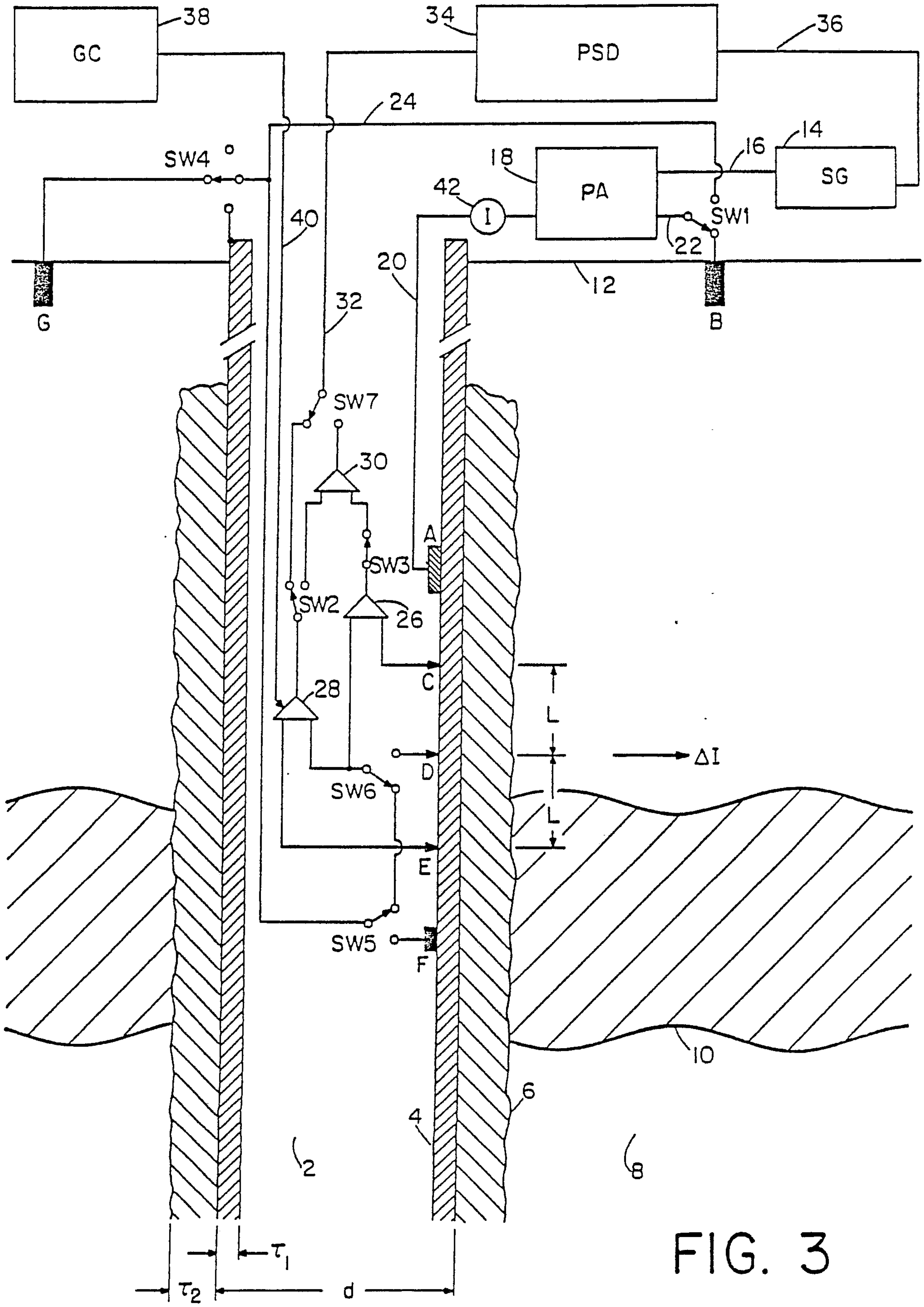


FIG. 2



GC
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SW7
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A
SW3
SW2
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C
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ΔI
SW6
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SW5
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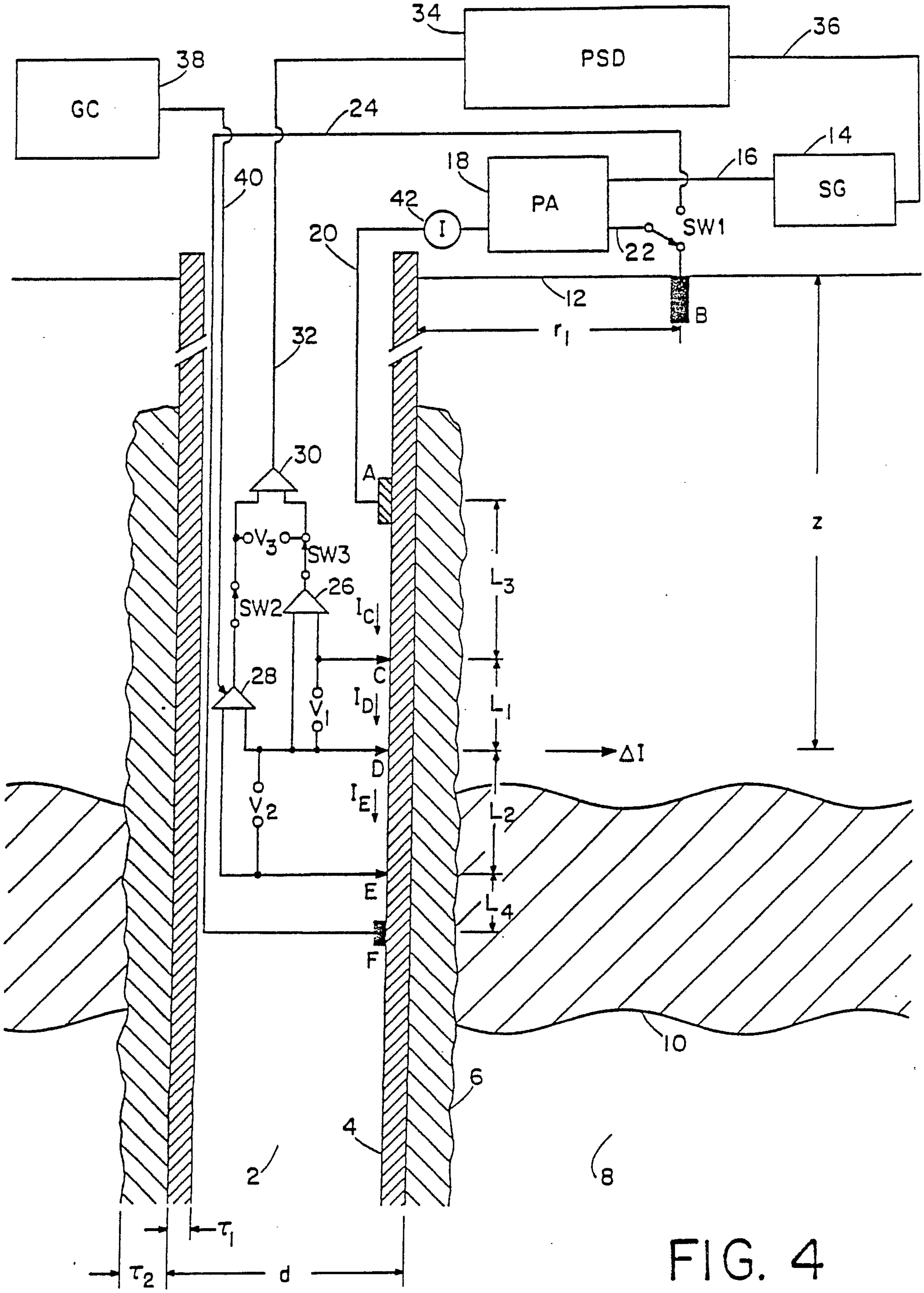
τ1
τ2
d

FIG. 3



PSD
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L_2
L_4
V_1
V_2
V_3
I_C
I_D
I_E
ΔI
τ_1
τ_2
d
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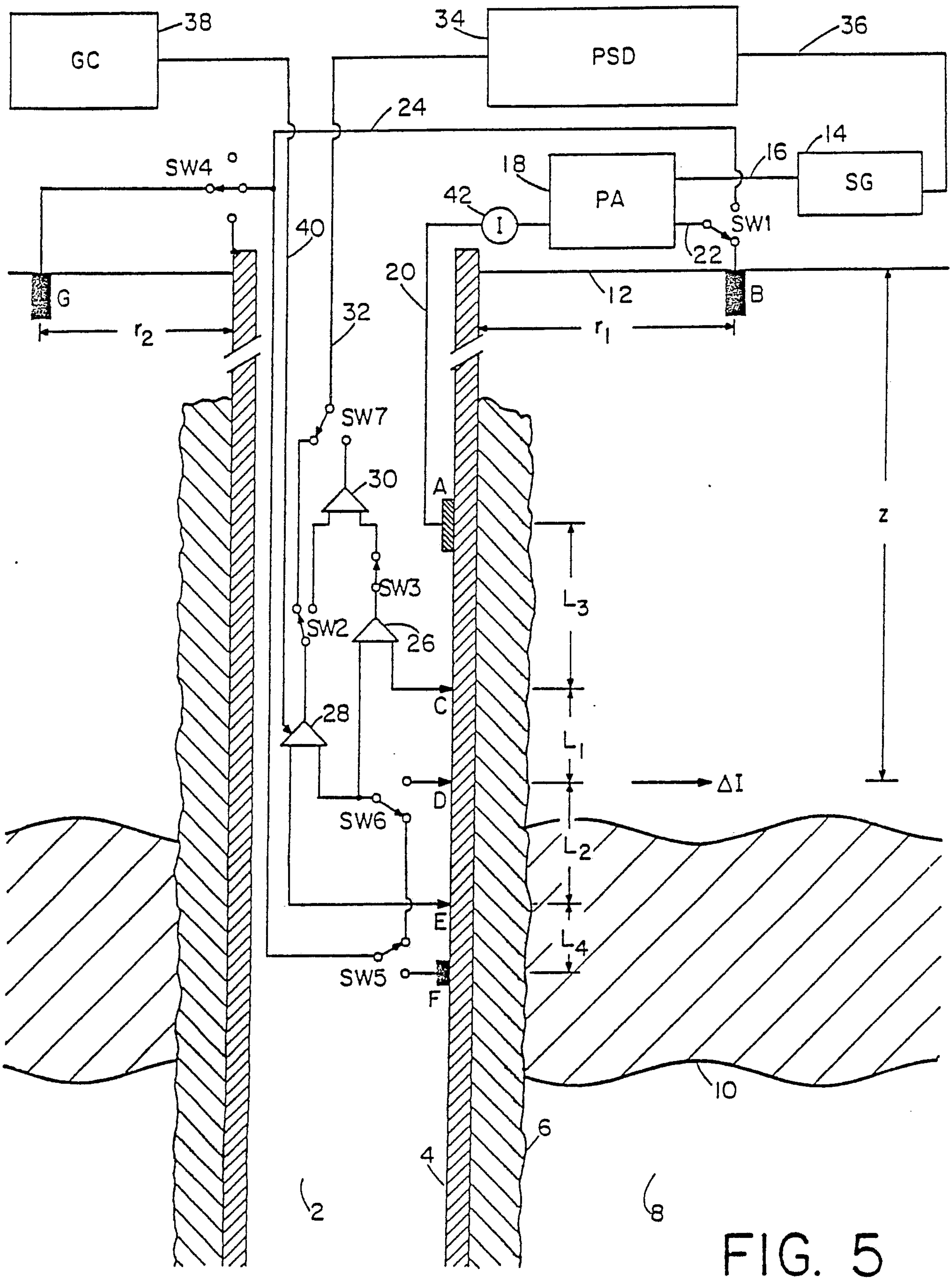
FIG. 4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B
r2
r1
32
SW7
30
A
z
SW3
L3
SW2
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C
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L1
D
ΔI
SW6
L2
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L4
SW5
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FIG. 5

6/26

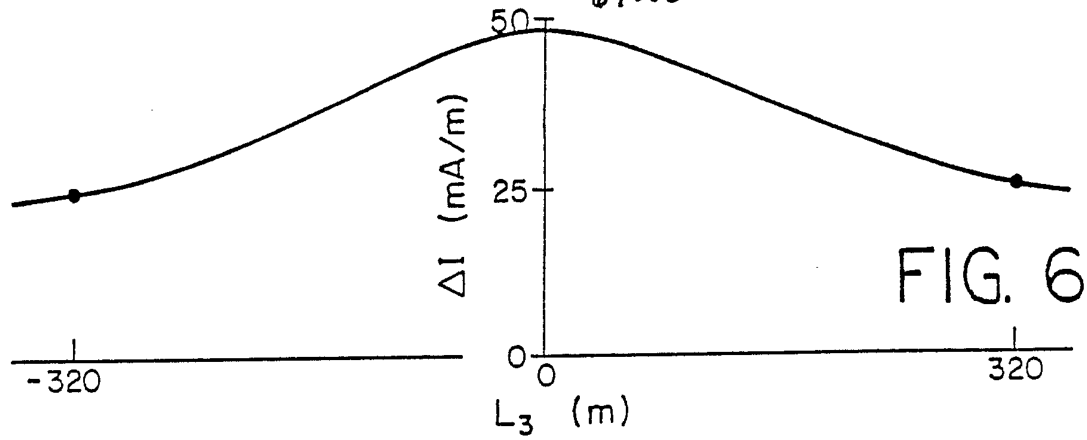


FIG. 6

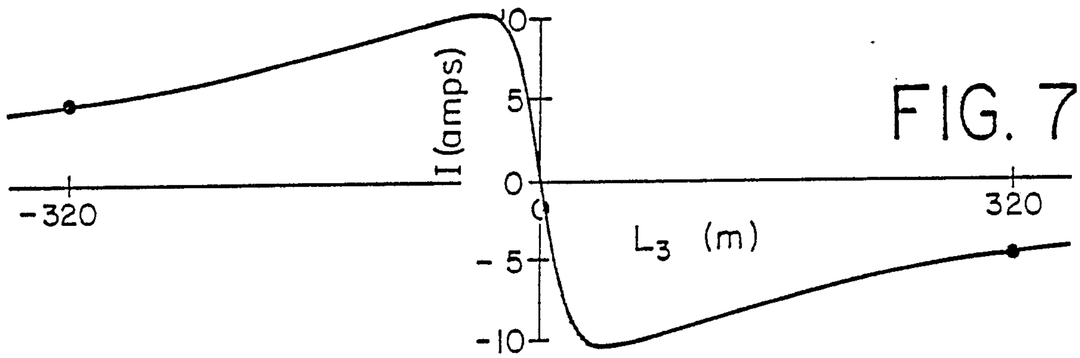


FIG. 7

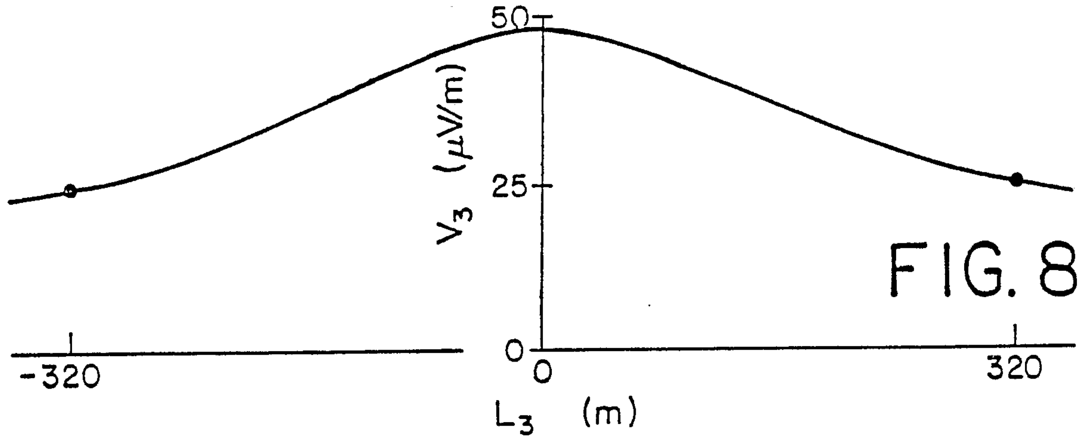


FIG. 8

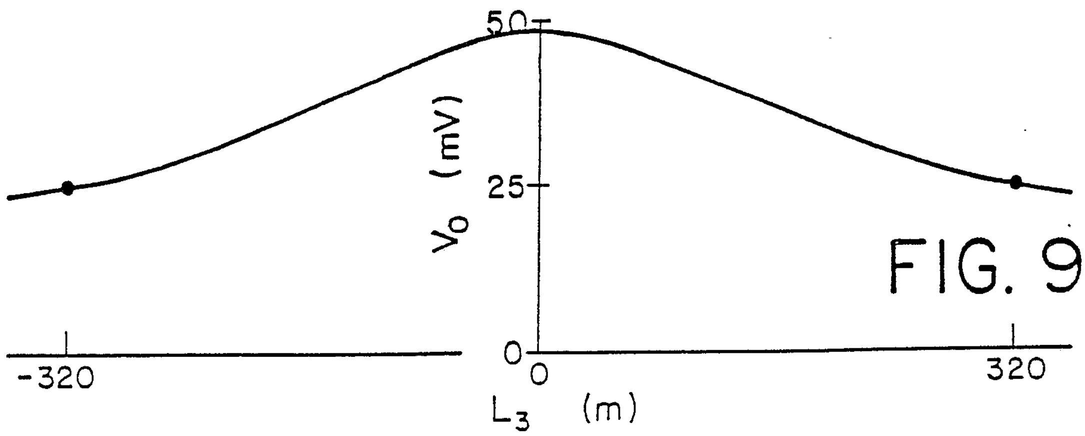


FIG. 9

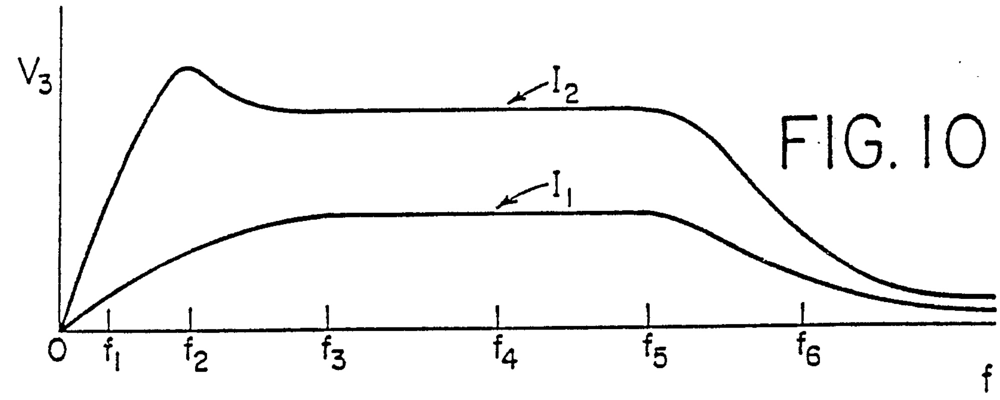


FIG. 10

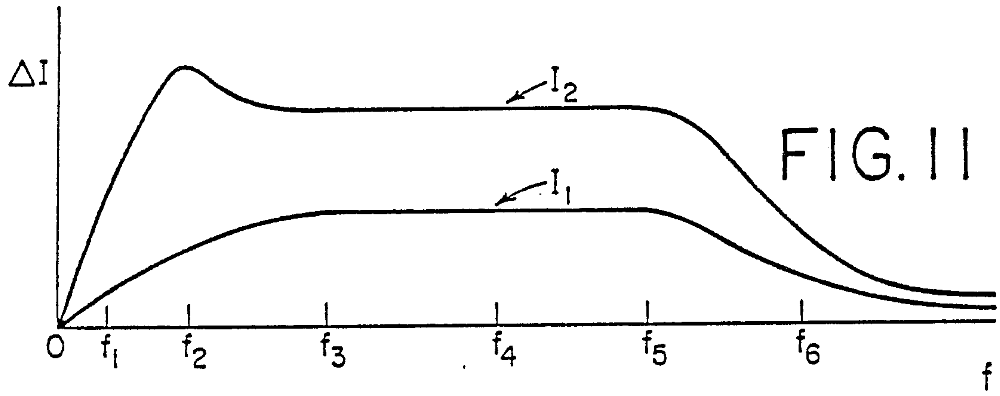


FIG. 11

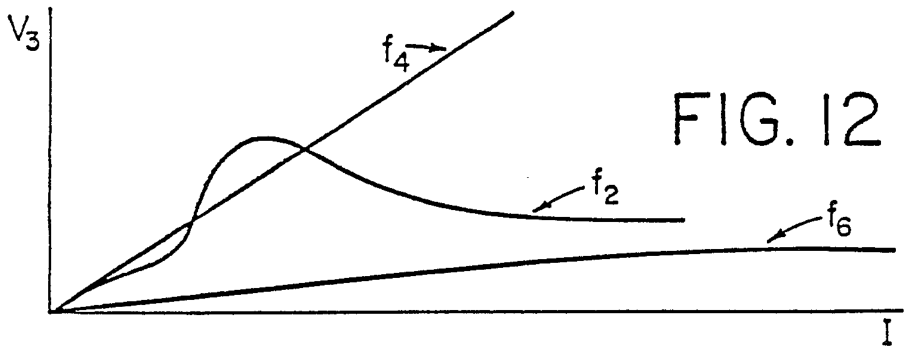


FIG. 12

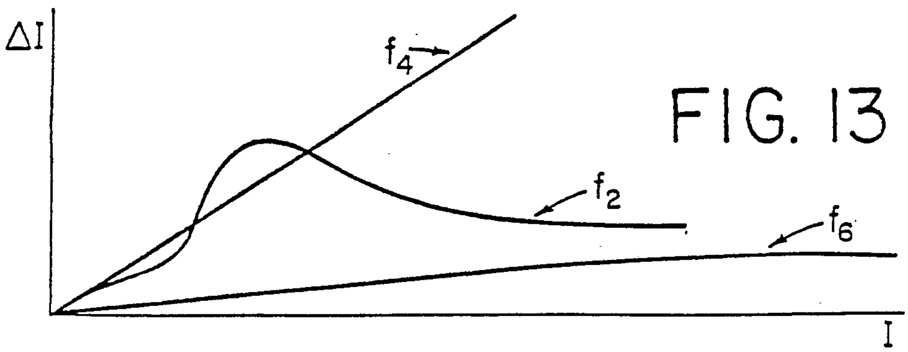


FIG. 13

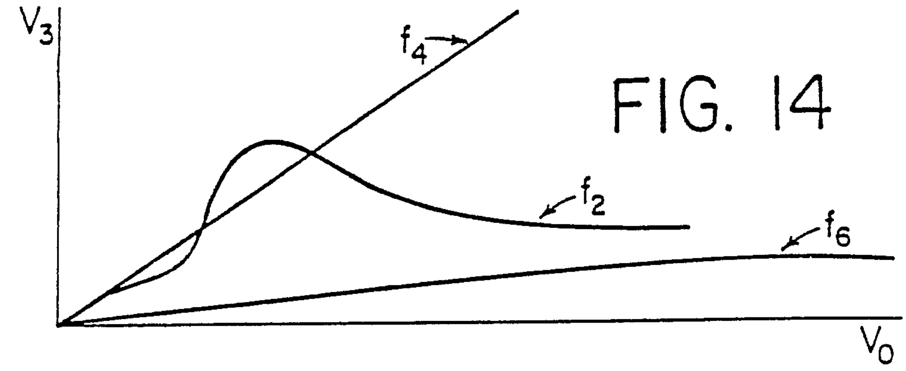


FIG. 14

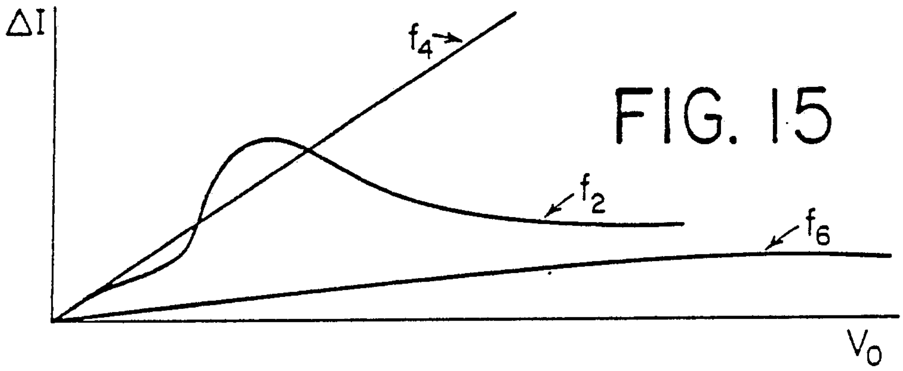


FIG. 15

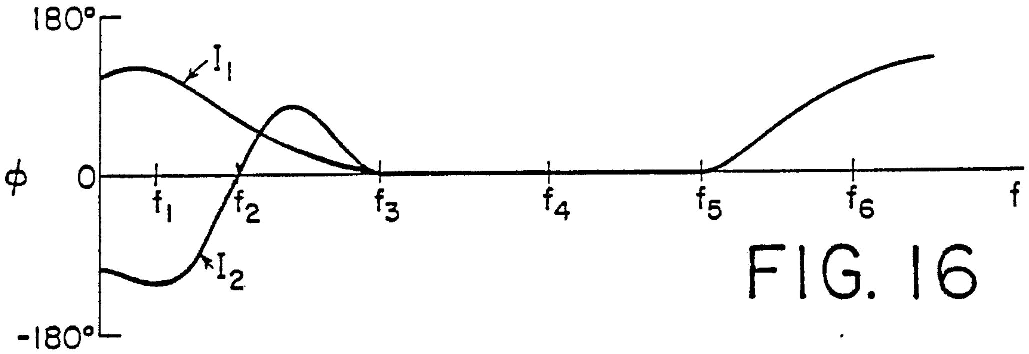


FIG. 16

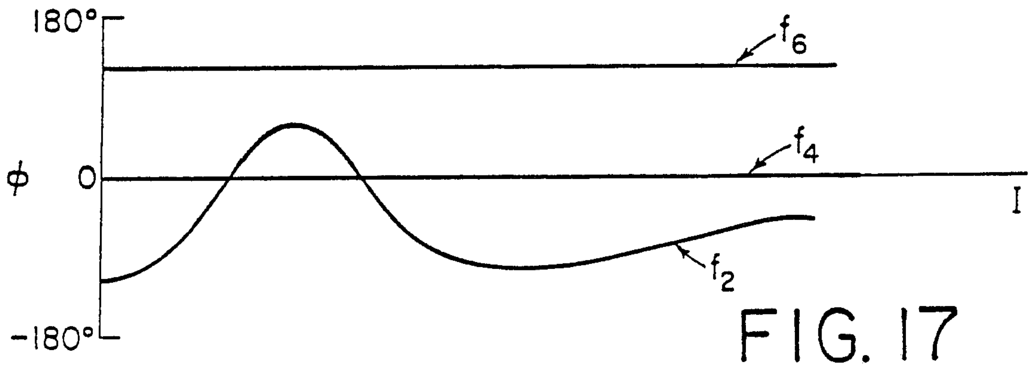


FIG. 17

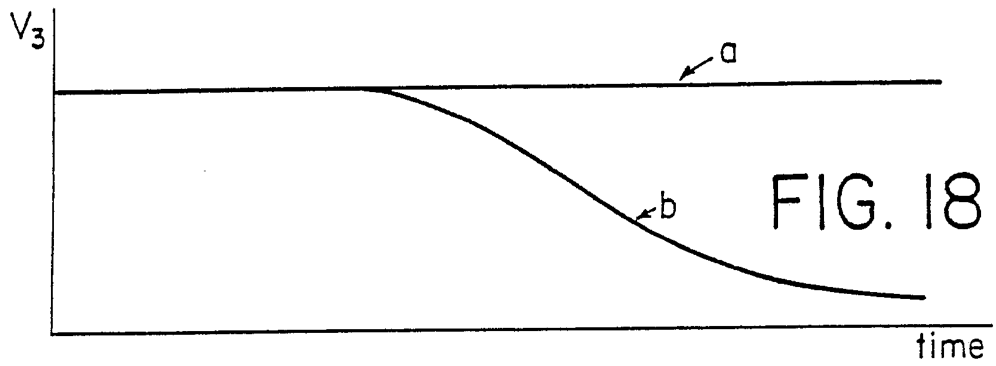


FIG. 18

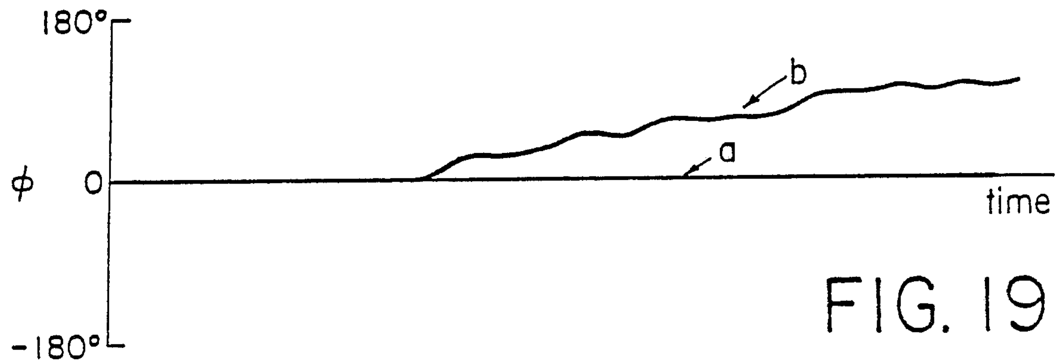


FIG. 19

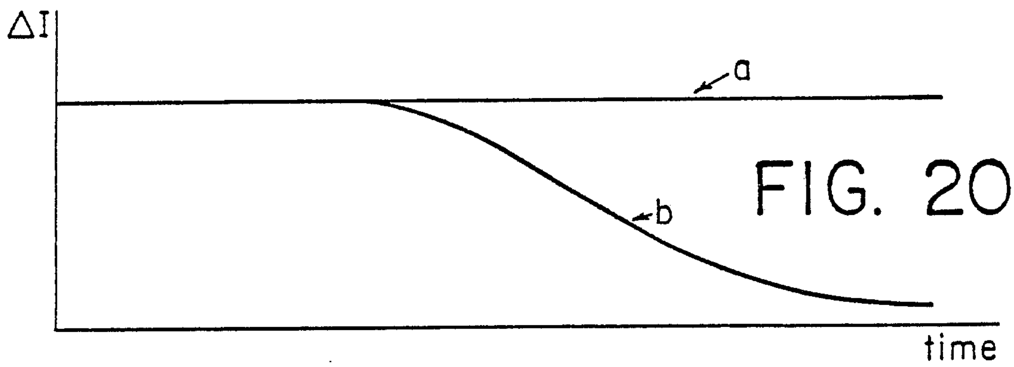


FIG. 20

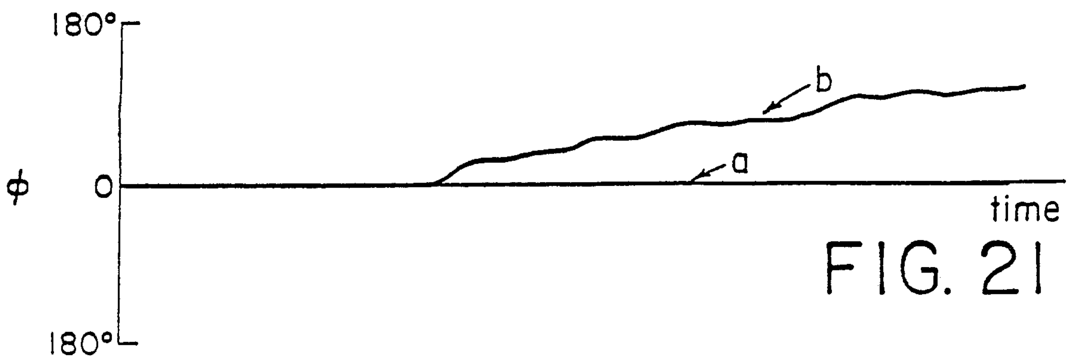
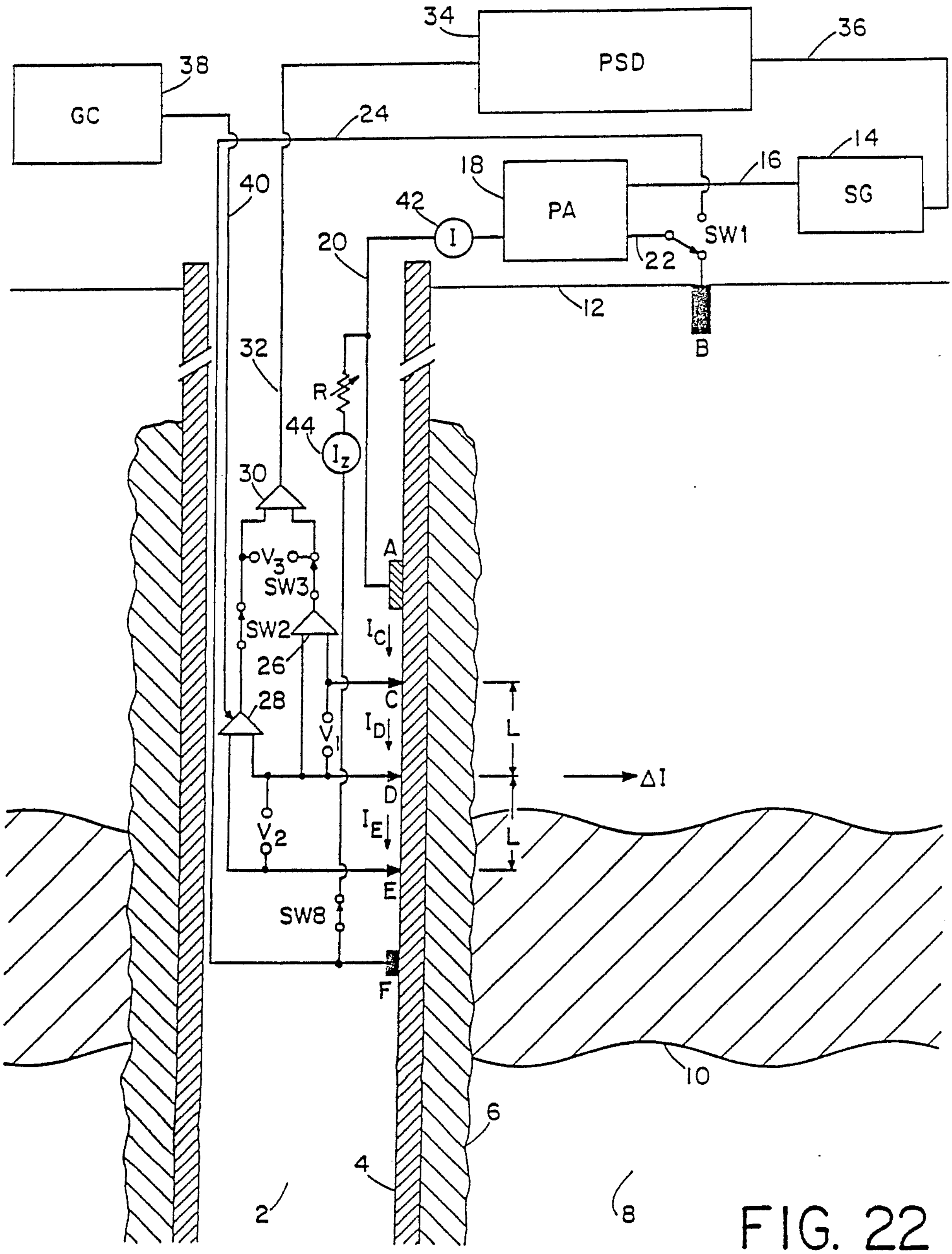


FIG. 21



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44
I_z
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A
V_3
SW3
SW2
26
I_C
28
C
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ΔI
I_E
V_2
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SW8
F
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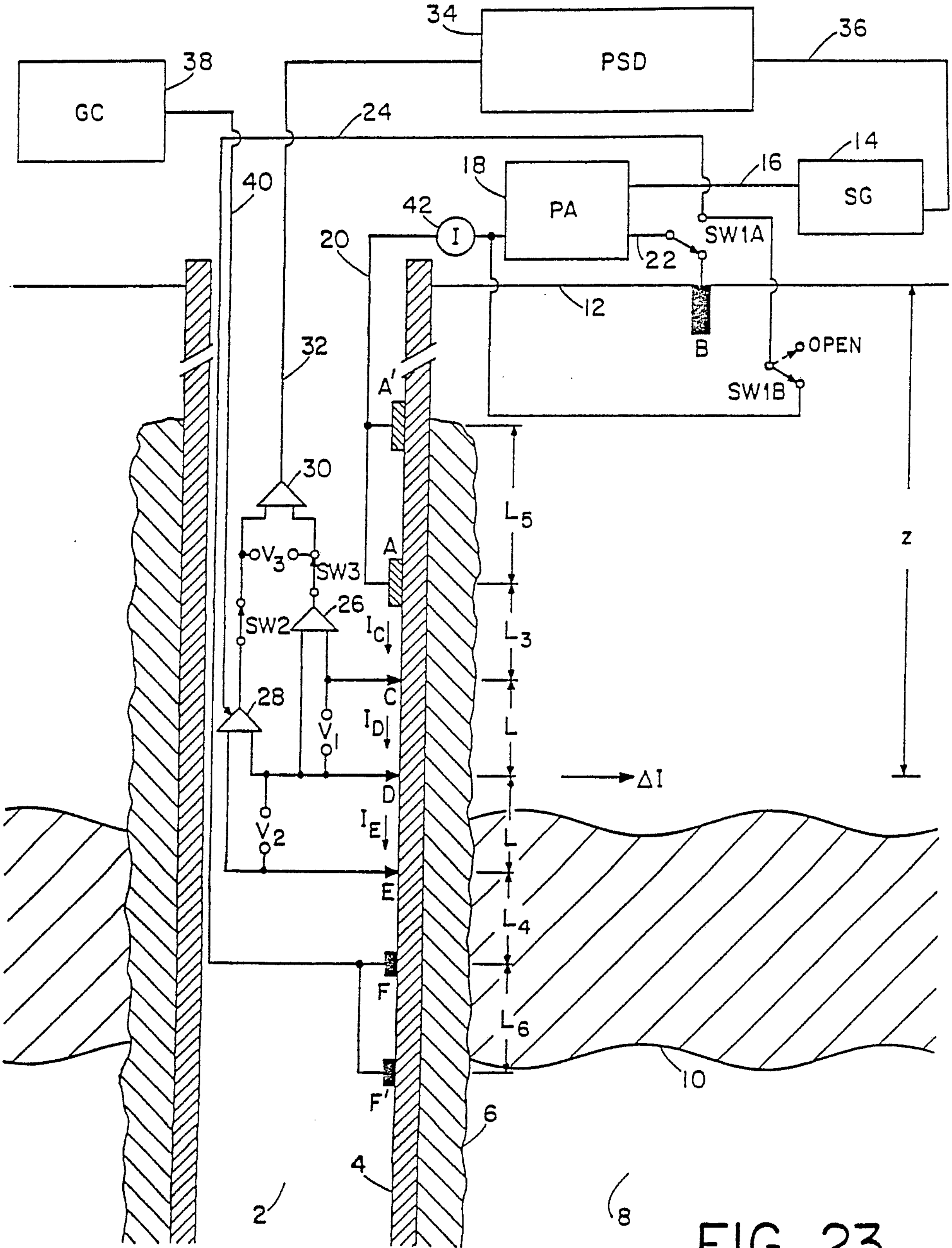
FIG. 22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A'
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L5
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V3
SW3
z
26
SW2
IC
L3
C
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ID
V1
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IE
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F'
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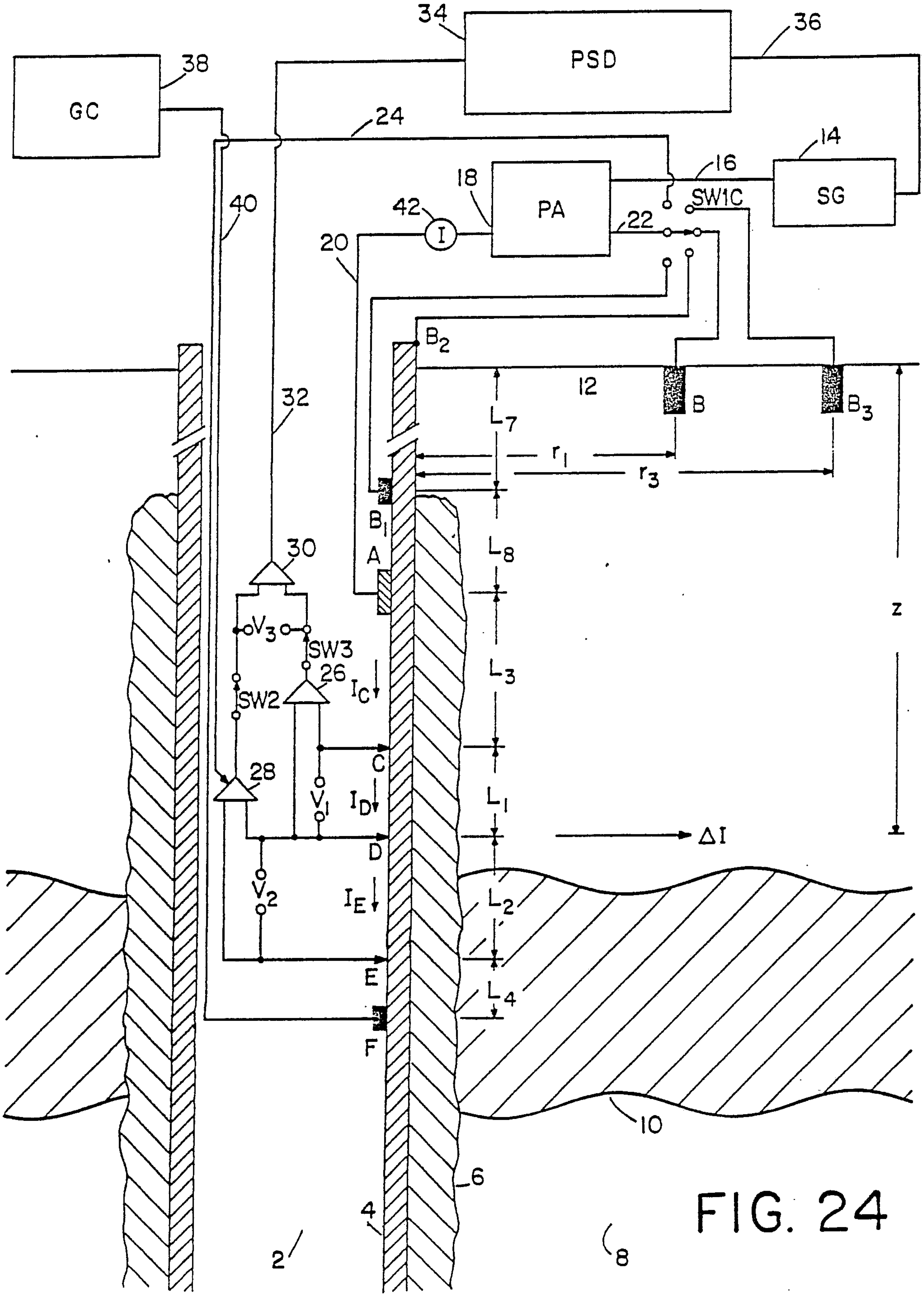
FIG. 23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SW3
26
IC
L3
SW2
C
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FIG. 24

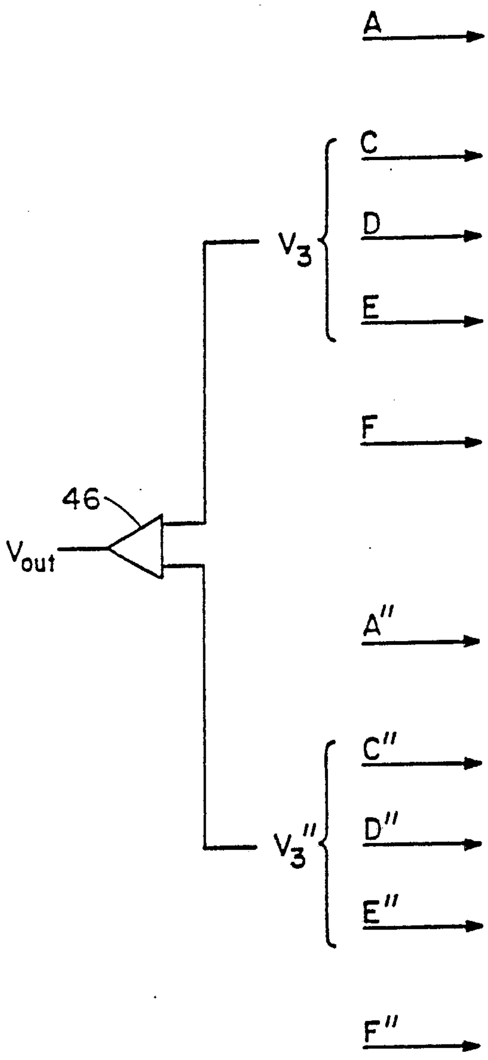

FIG. 25

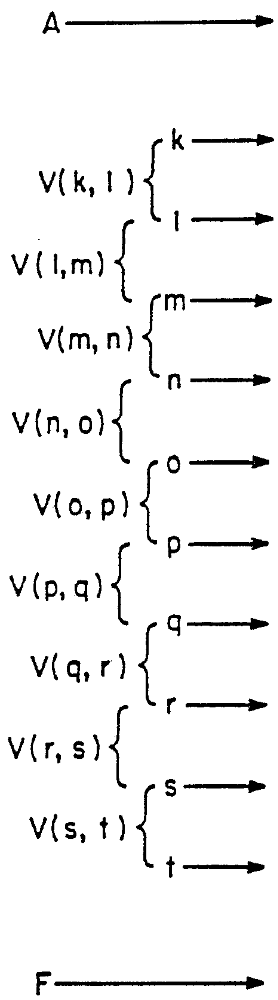

FIG. 26

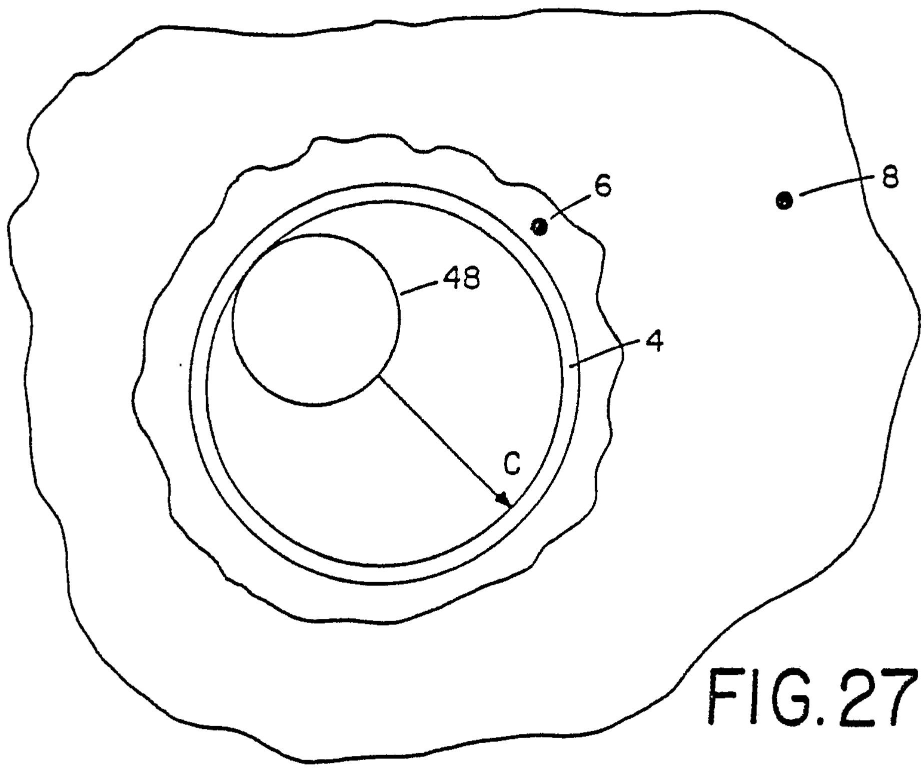

FIG. 27

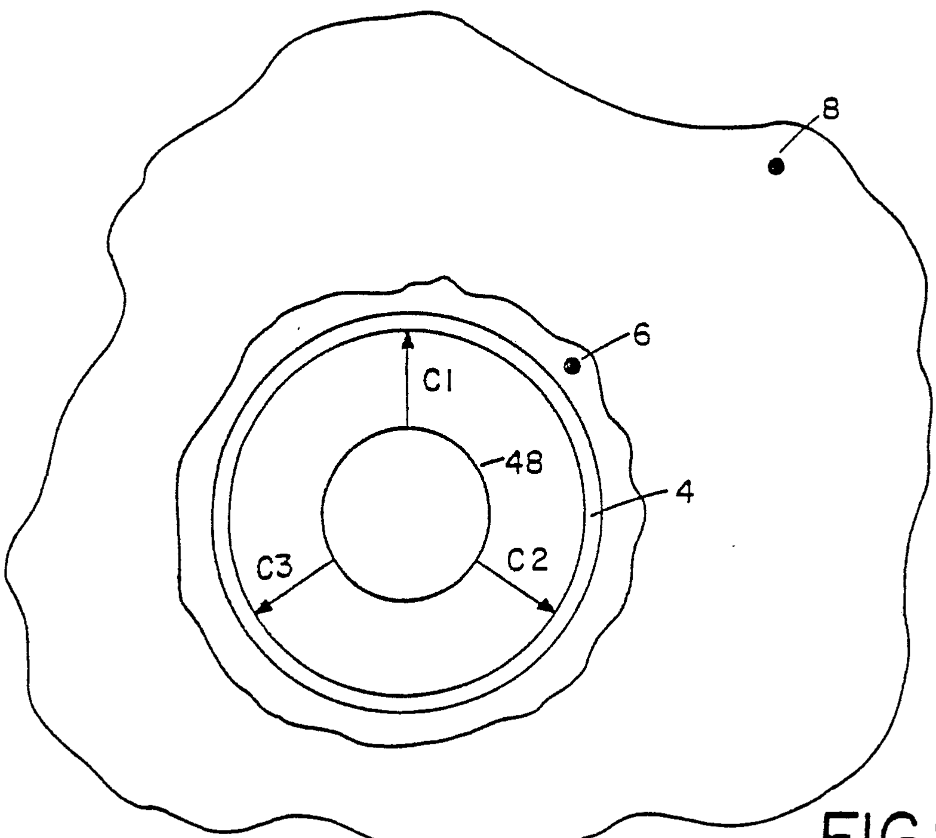

FIG.28

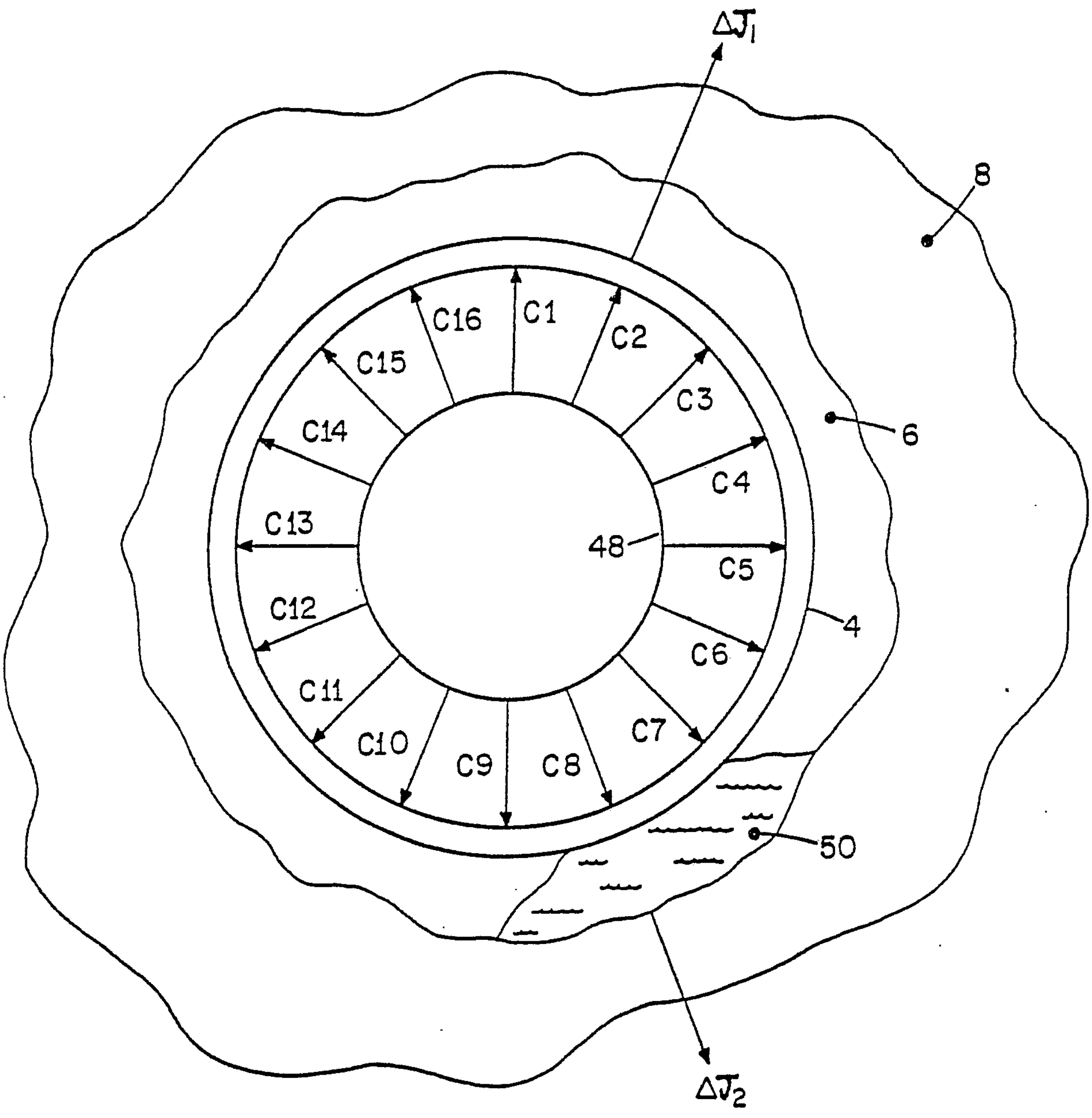
ΔJ1
8
C1
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FIG. 29

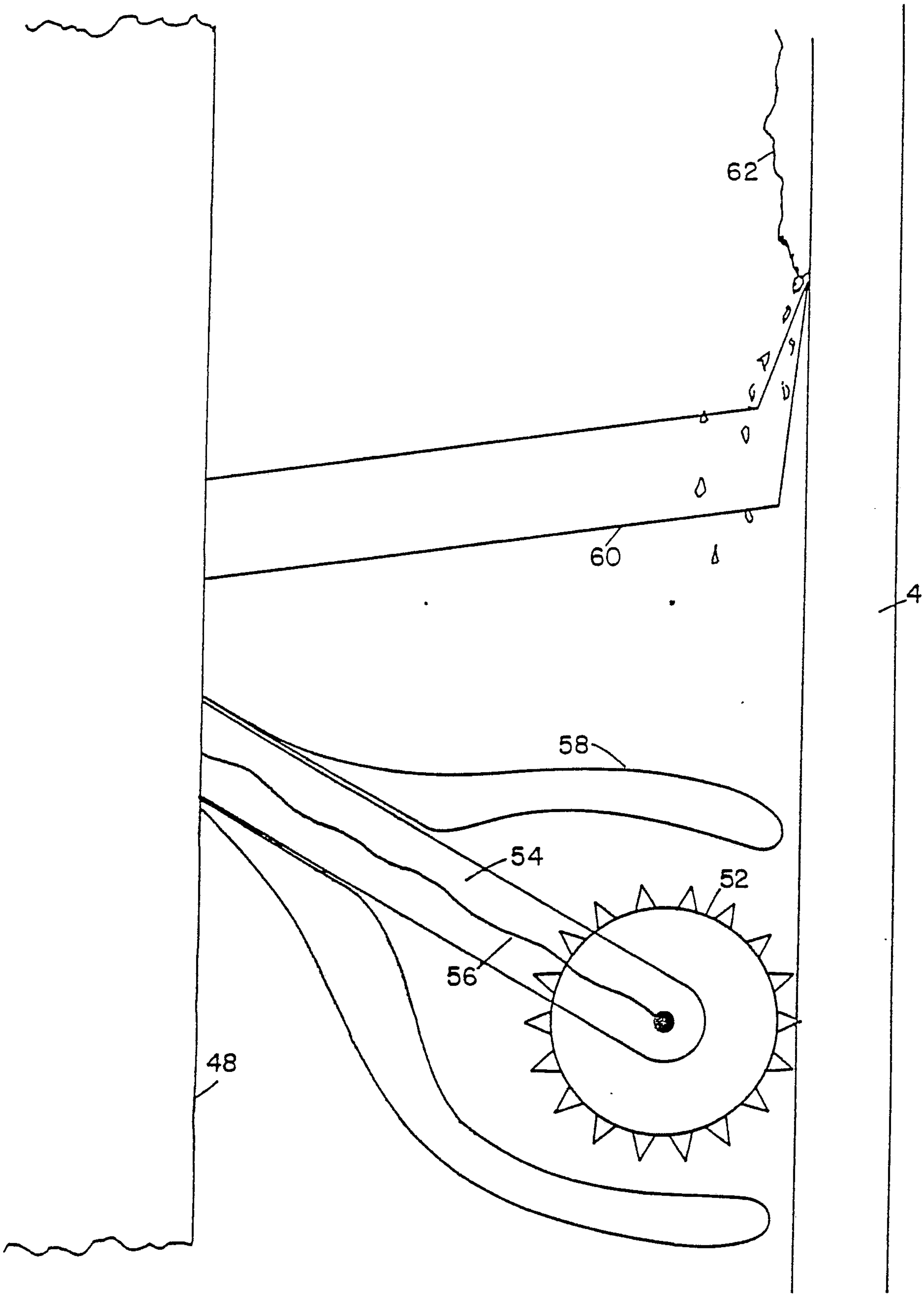
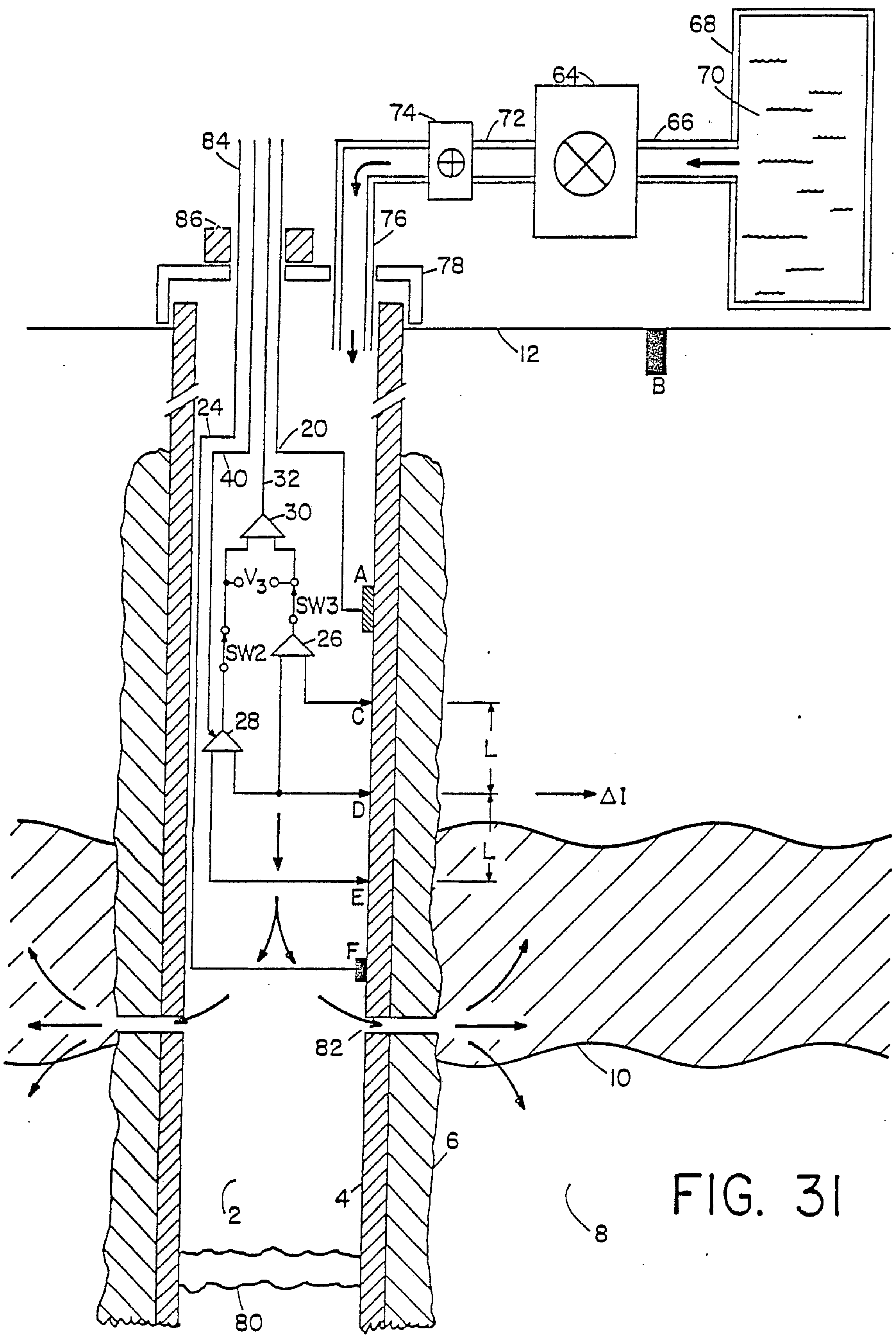


FIG. 30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V3
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SW2
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L
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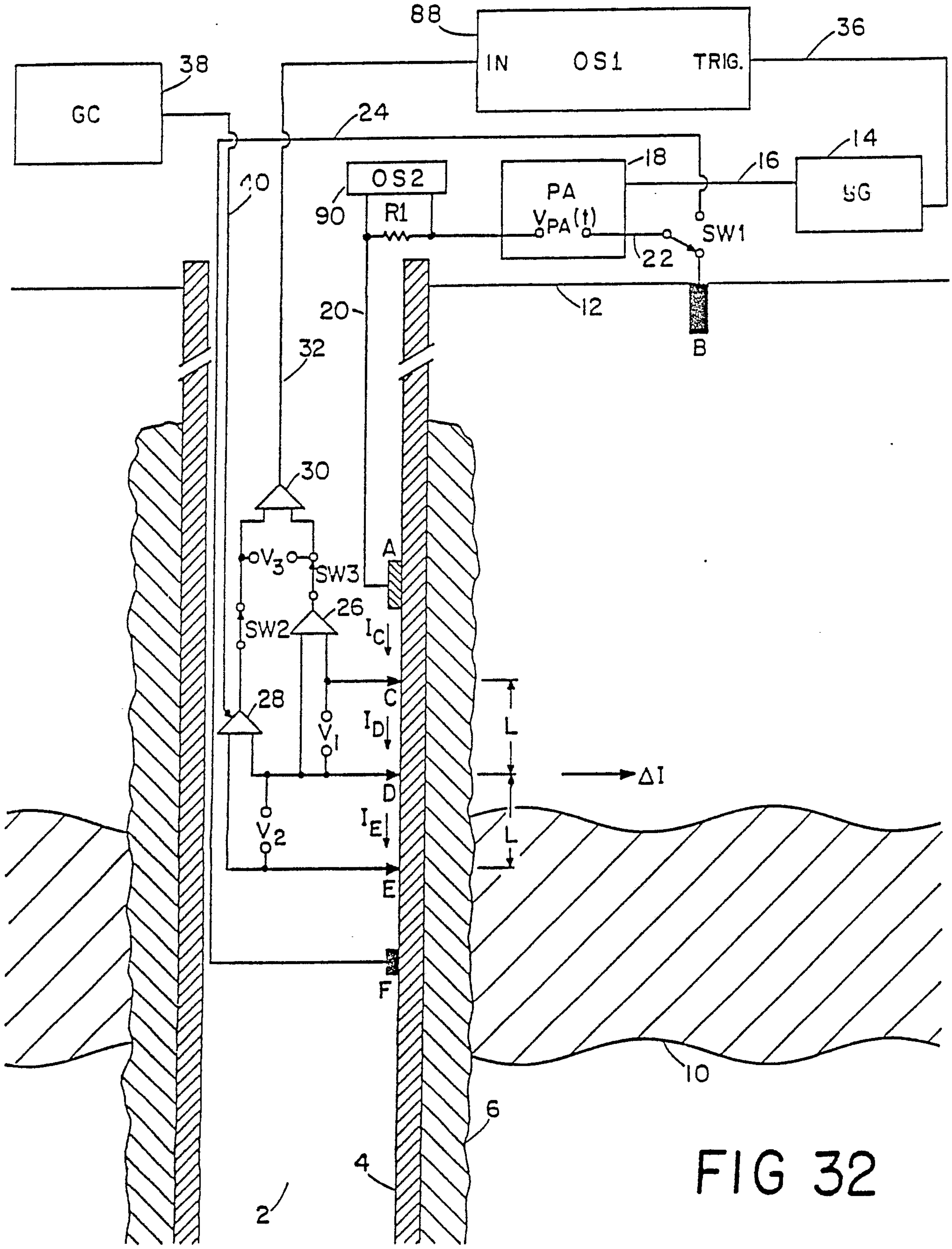
80

FIG. 31



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SW1
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V_3
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SW2
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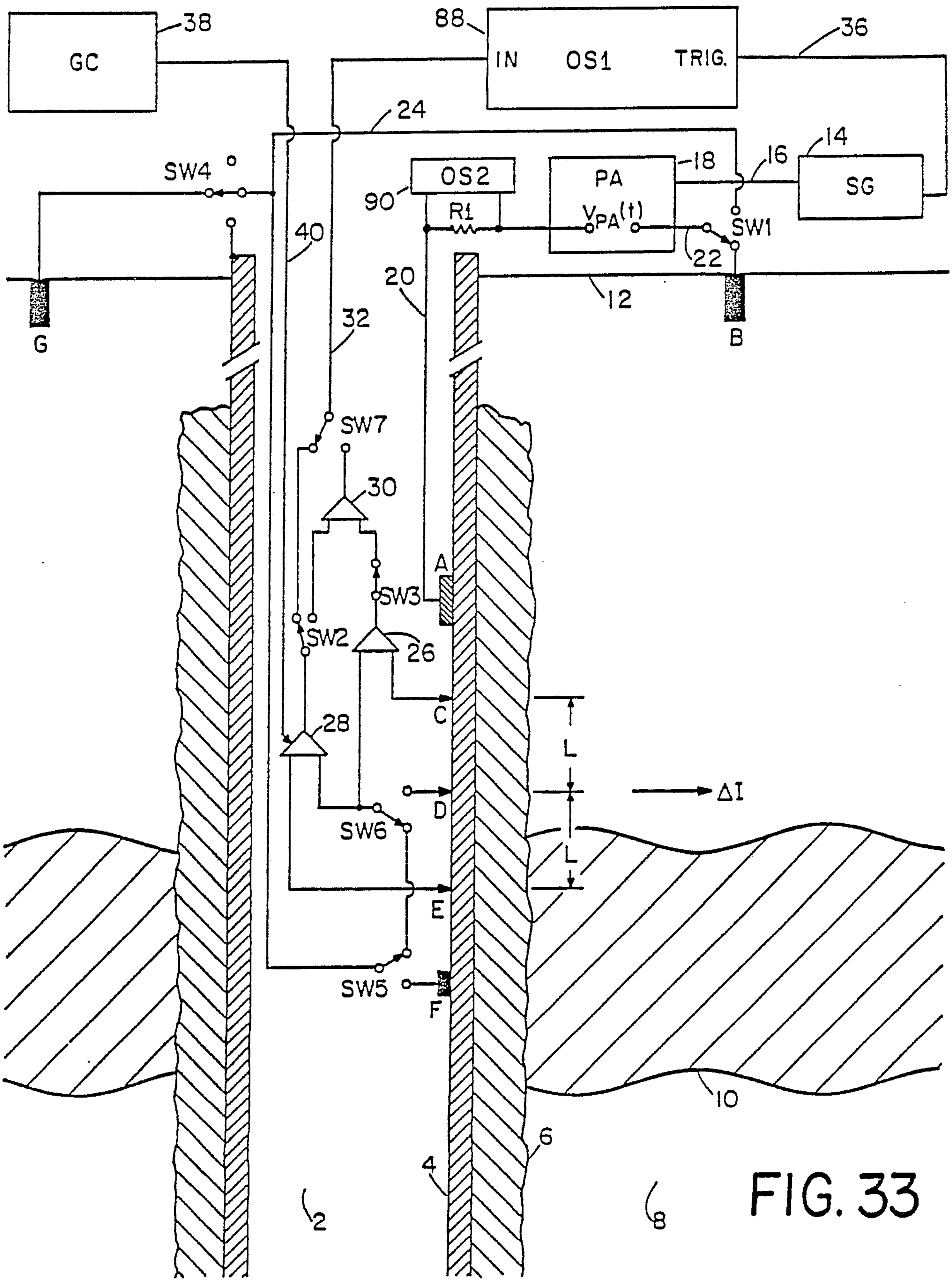
FIG 32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SW7
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A
SW3
SW2
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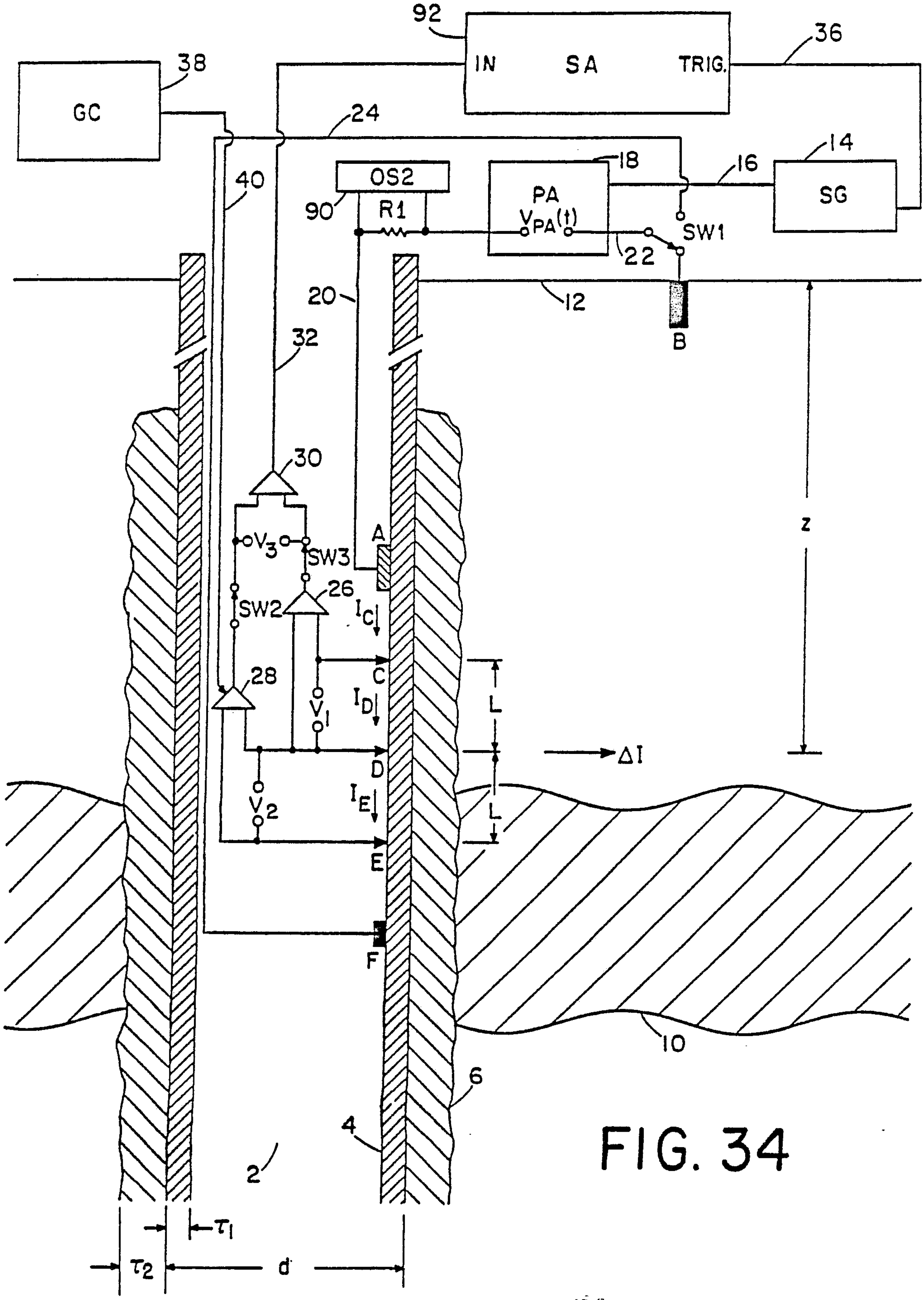
FIG. 33



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V_3
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SW2
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V_1
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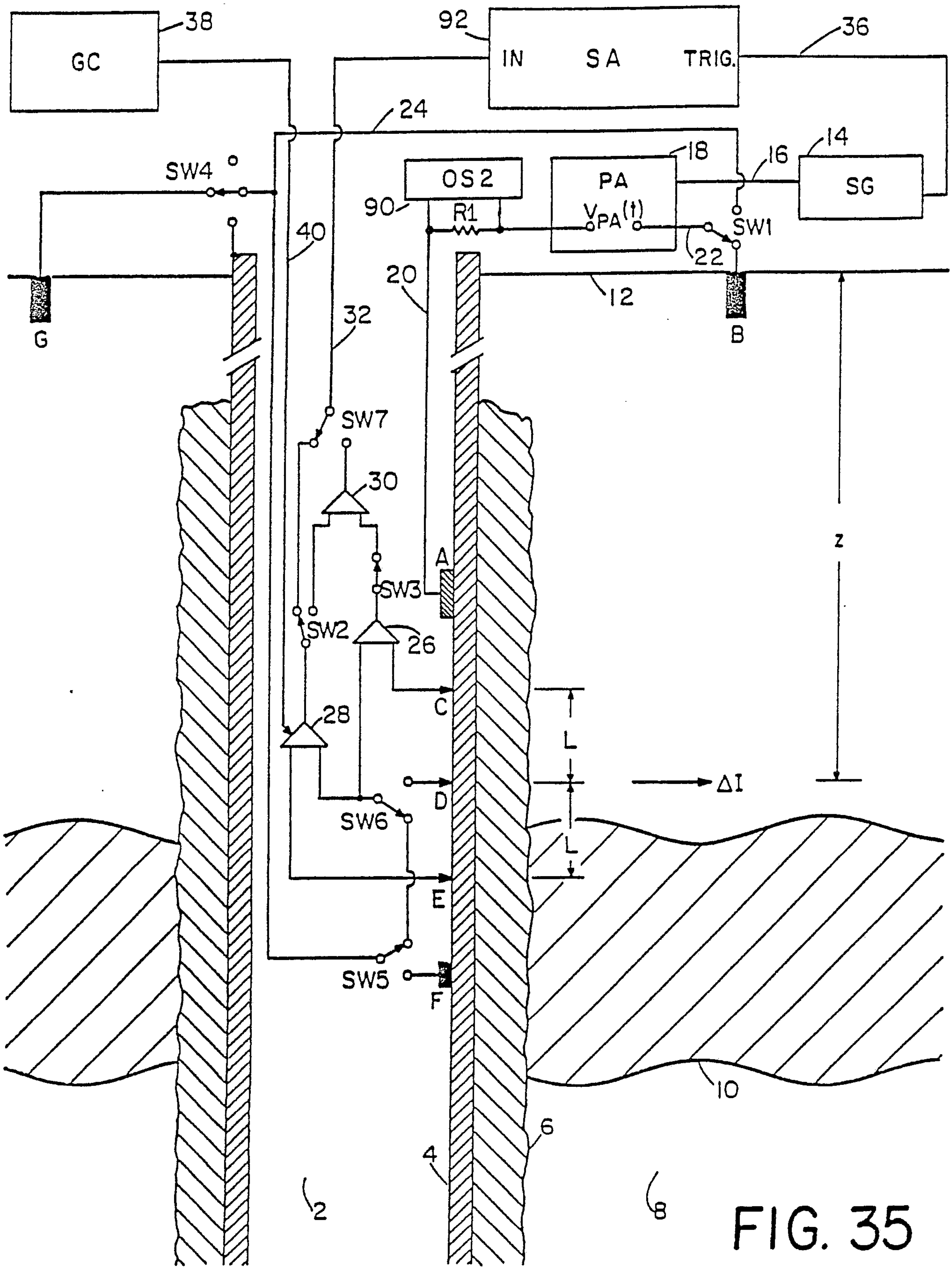
τ_1
τ_2
d

FIG. 34



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R1
$V_{PA}(t)$
SW1
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SW7
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A
SW3
SW2
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C
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L
z
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ΔI
SW6
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SW5
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FIG. 35

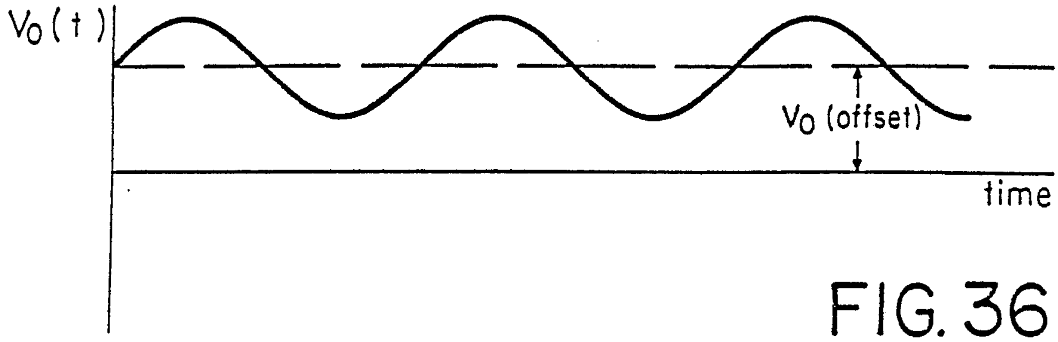

FIG. 36

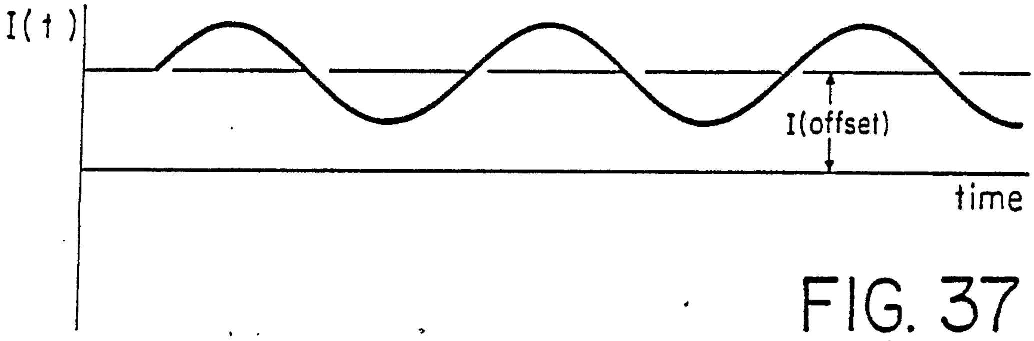

FIG. 37

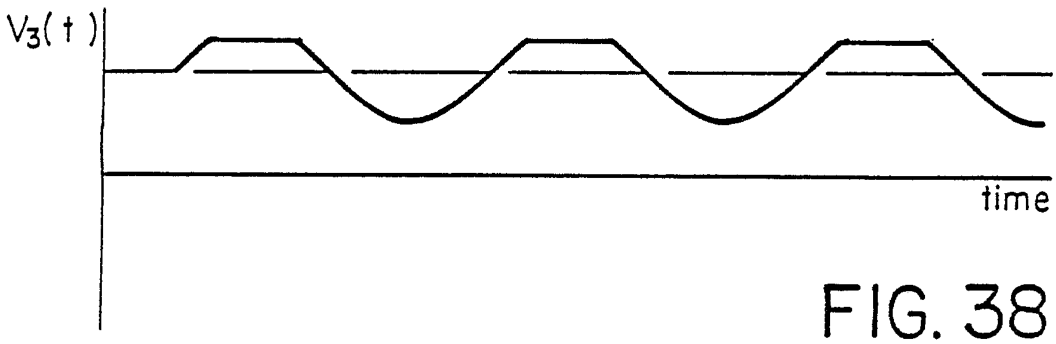

FIG. 38

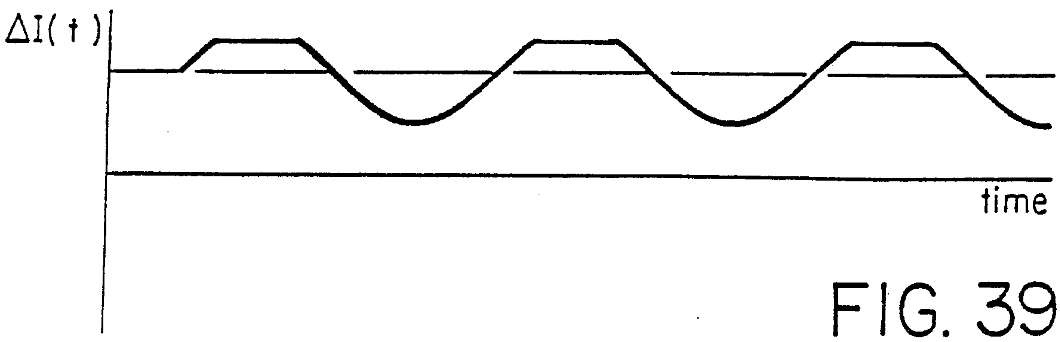

FIG. 39

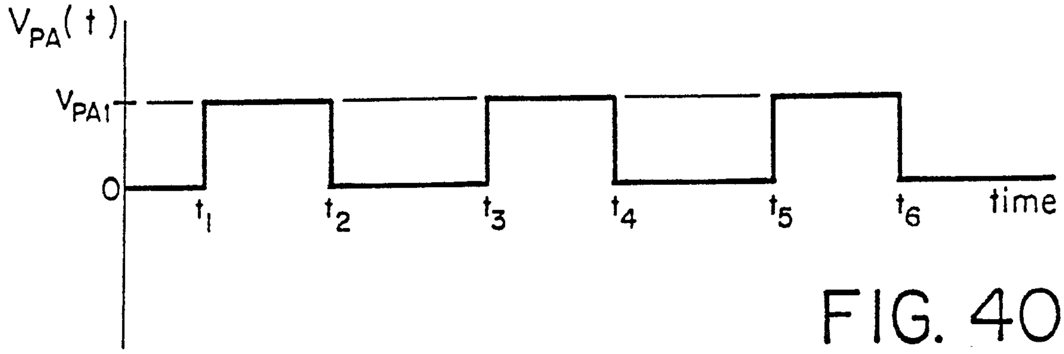

FIG. 40

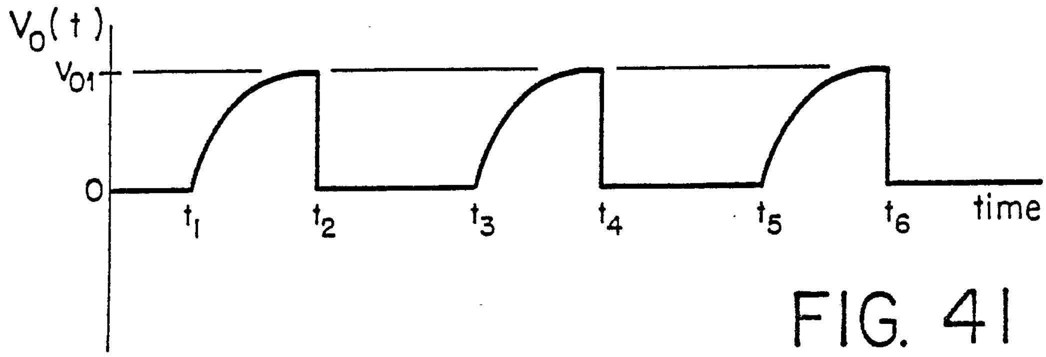

FIG. 41

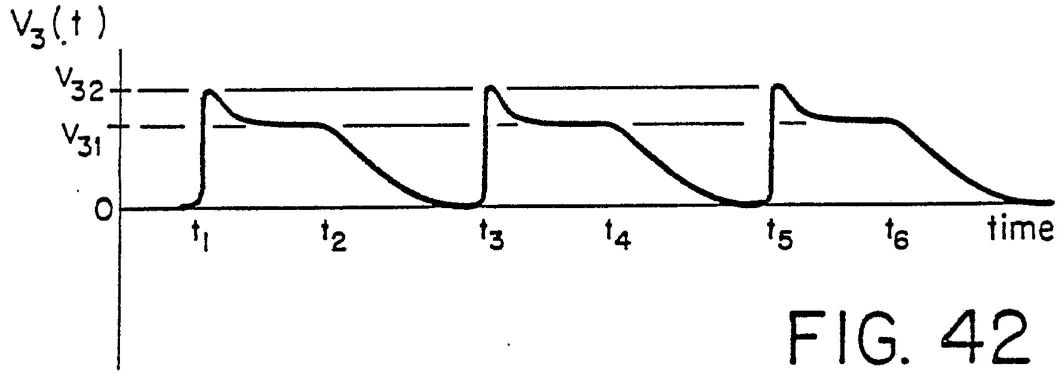

FIG. 42

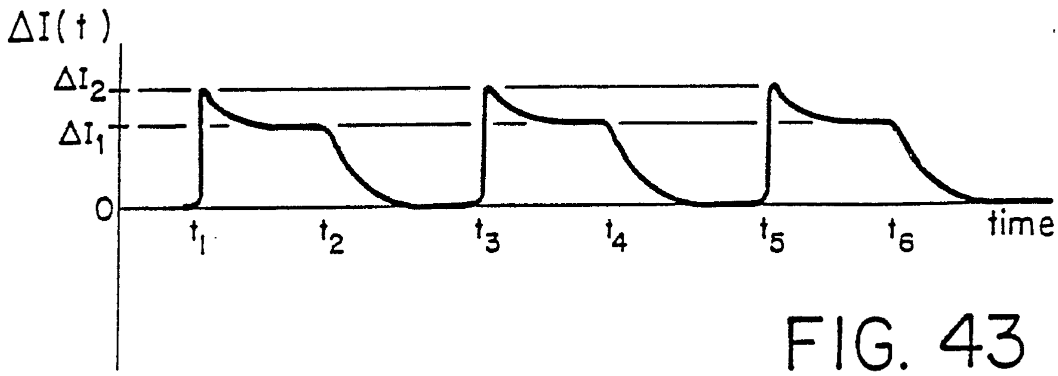

FIG. 43

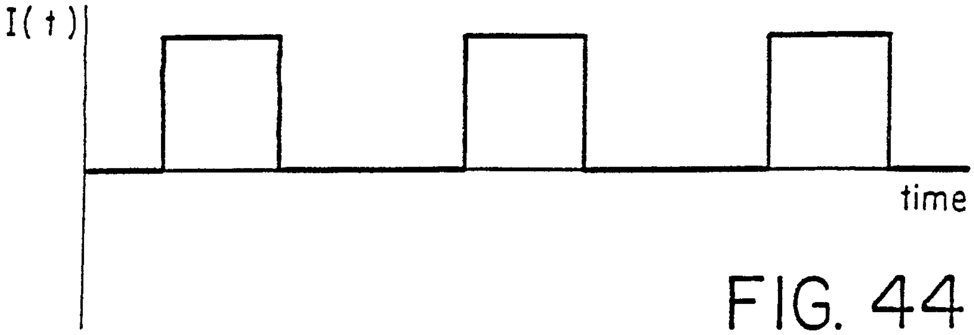

FIG. 44

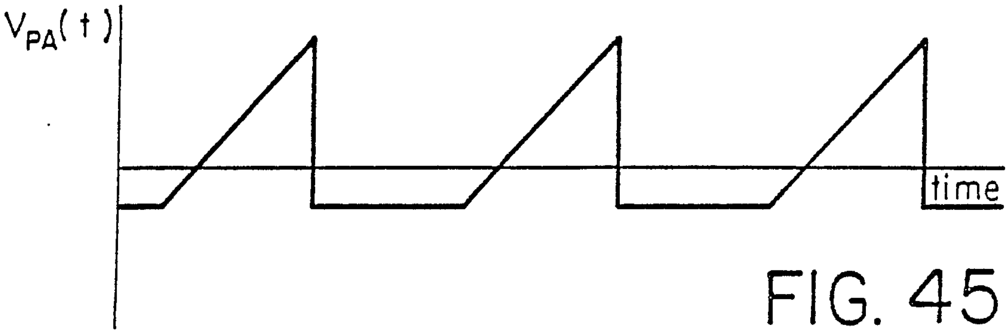

FIG. 45

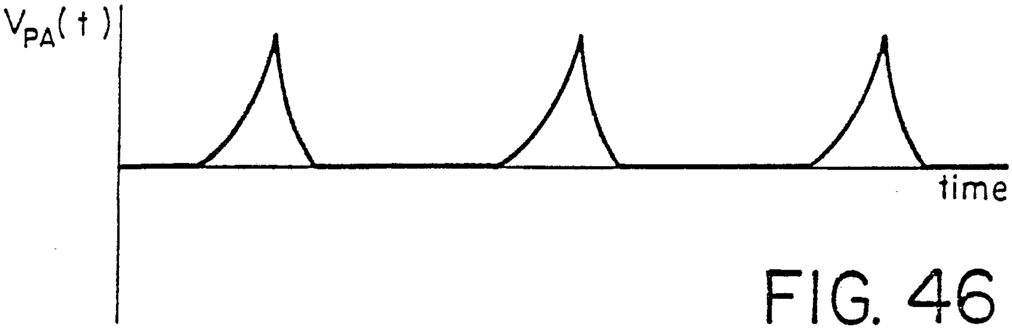

FIG. 46

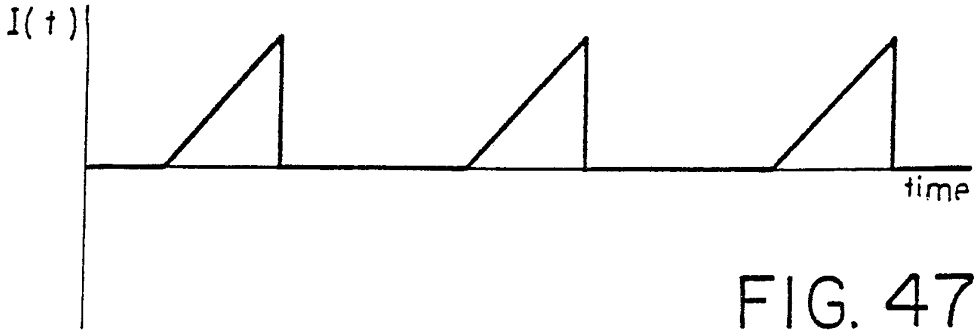

FIG. 47

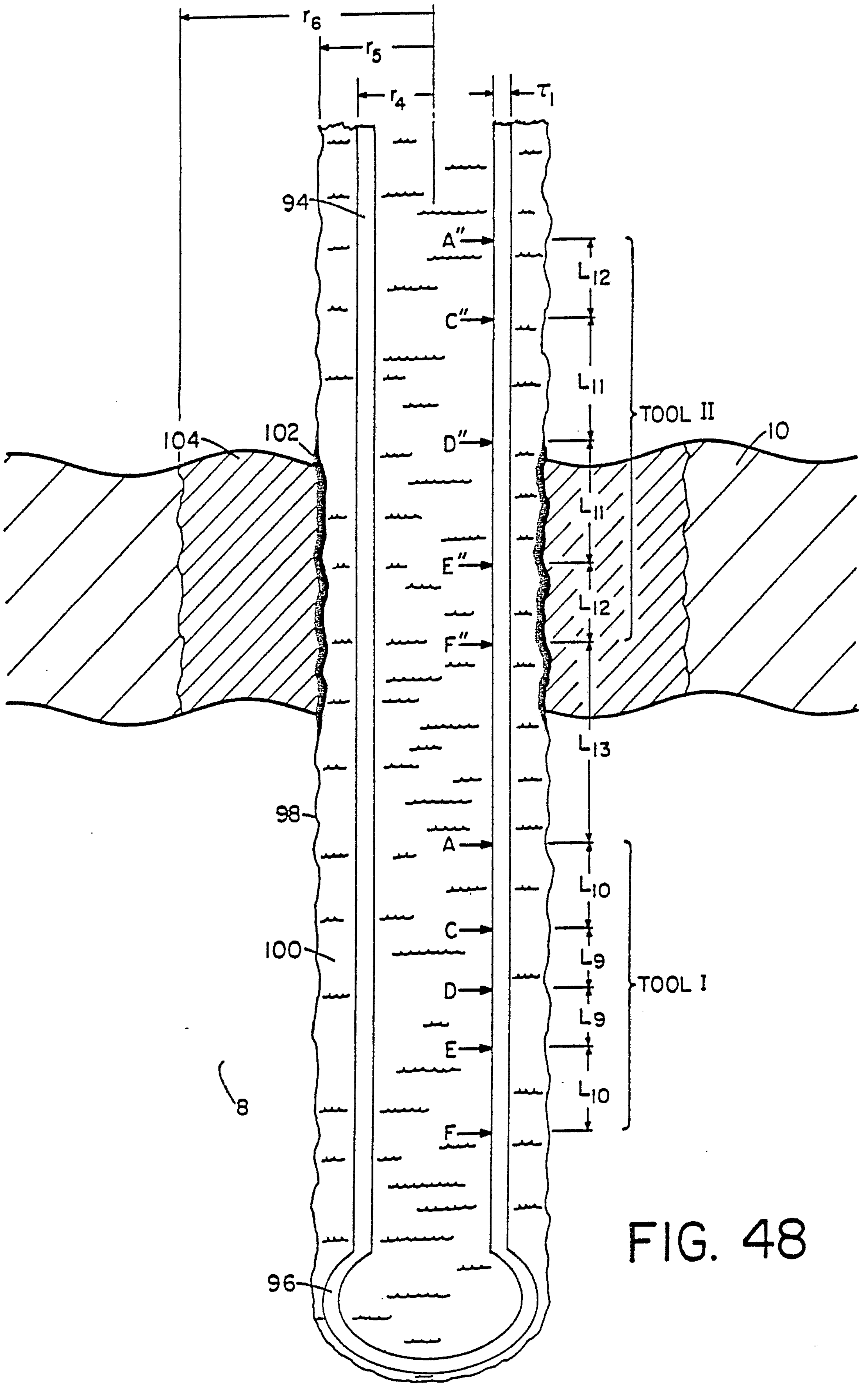
r6
r5
r4
τ1
94
A''
L12
C''
L11
TOOL II
104
102
D''
10
L11
E''
L12
F''
L13
98
A
L10
C
L9
100
TOOL I
D
L9
E
L10
8
F
96

FIG. 48

INTERNATIONAL SEARCH REPORT

International Application No PCT/US87/02861

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) [3]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC(4): G01V 3/20
US CL: 324/368

II. FIELDS SEARCHED

Minimum Documentation Searched [4]

Classification System	Classification Symbols
US	324/347-375

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched [5]

III. DOCUMENTS CONSIDERED TO BE RELEVANT [14]

Category *	Citation of Document, [16] with indication, where appropriate, of the relevant passages [17]	Relevant to Claim No. [18]
A	US, A, 1,940,340, (Zuschlag), 10 December 1933	1-92
A	US, A, 1,997,163, (Zuschlag), 9 April 1935	1-92
A	US, A, 2,613,247, (Lee), 7 October 1952	1-92
A	US, A, 2,165,213, (Blau et al), 11 July 1939	1-92
A	US, A, 2,371,658, (Stewart), 20 March 1945	1-92
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A	US, A, 2,400,593, (Neufeld), 21 May 1946	1-92
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A	US, A, 2,297,754, (Ernis), 6 October 1942	1-92
A	US, A, 2,414,194, (Ernis), 14 January 1947	1-92
A	US, A, 2,224,635, (Lipson), 10 December 1940	1-92

* Special categories of cited documents: [15]

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search [2]	Date of Mailing of this International Search Report [2]
28 January 1988	23 MAR 1988
International Searching Authority [1]	**Signature of Authorized Officer [10]**
ISA/USA	Warren S. Edmonds

International Application No. PCT/US87/02861

FURTHER INFORMATION CONTINUED FROM THE SECOND SHEET

A	US, A, 2,222,149, (Lipson), 19 November 1940	1-92
A	US, A, 2,922,101, (Mayes), 19 January 1960	1-92
A	US, A, 2,790,137, (Mayes), 23 April 1957	1-92
A	US, A, 2,587,518, (Pearson), 26 February 1952	1-92

V.☐ OBSERVATIONS WHERE CERTAIN CLAIMS WERE FOUND UNSEARCHABLE [10]

This international search report has not been established in respect of certain claims under Article 17(2) (a) for the following reasons:

1.☐ Claim numbers . . because they relate to subject matter [12] not required to be searched by this Authority, namely:

2.☐ Claim numbers . . . . , because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out [13], specifically:

VI.☐ OBSERVATIONS WHERE UNITY OF INVENTION IS LACKING [11]

This International Searching Authority found multiple inventions in this international application as follows:

1.☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims of the international application.

2.☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims of the international application for which fees were paid, specifically claims:

3.☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claim numbers:

4.☐ As all searchable claims could be searched without effort justifying an additional fee, the International Searching Authority did not invite payment of any additional fee.

Remark on Protest

☐ The additional search fees were accompanied by applicant's protest.

☐ No protest accompanied the payment of additional search fees.