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DIVISION DE NUEVAS CREACIONES

SUPERINTENDENCIA DE INDUSTRIA Y COMERCIO

Bogotá, D.C.

Re.: Código 02-01-329
Expediente No. 01-33.358
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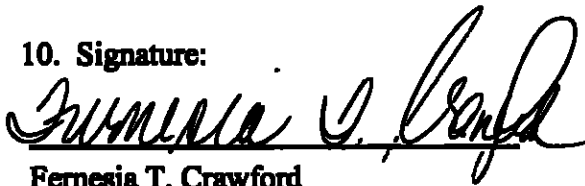
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APPLICATION NUMBER: 60/200,856

FILING DATE: May 01, 2000



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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.63 (c).

INVENTOR(S)					
Given Name (first and middle (if any))	Family Name or Surname	Residence (City and other State or Foreign Country)			
Edward	Nichols	Berkeley, California			
Huntly F.	Morrison	Berkeley, California			

☐ Additional inventors are being named on the _____ separately numbered sheets attached hereto

TITLE OF THE INVENTION (250 characters max)

A PERMANENT ELECTROMAGNETIC SYSTEM FOR MEASURING FORMATION
RESISTIVITY ADJACENT TO AND BETWEEN Cased WELLS

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ENCLOSED APPLICATION PARTS (check all that apply)

☒ Specification Number of Pages **20** ☐ Small Entity Statement

☒ Drawing(s) Number of Sheets **8** ☐ Other (specify)

METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT (check one)

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Respectfully submitted,

SIGNATURE *Kenneth C. Brooks*Date **05/01/00**TYPED or PRINTED NAME **Kenneth C. Brooks**REGISTRATION NO.
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Deposit Number:

EMI-00-02-03**USE ONLY FOR FILING A PROVISIONAL APPLICATION FOR PATENT**

This collection of information is required by 37 CFR 1.61. The information is used by the public to file (and by the PTO to process) a provisional application. Confidentiality is governed by 38 U.S.C. 122 and 37 CFR 1.14. This collection is estimated to take 8 hours to complete, including gathering, preparing, and submitting the complete provisional application to the PTO. Time will vary depending upon the individual case. Any comments on the amount of time you require to complete this form and/or suggestions for reducing this burden, should be sent to the Chief Information Officer, U.S. Patent and Trademark Office, U.S. Department of Commerce, Washington, D.C., 20231. DO NOT SEND FEES OR COMPLETED FORMS TO THIS ADDRESS. SEND TO: Box Provisional Application, Assistant Commissioner for Patents, Washington, D.C., 20231.

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Docket No.: EMI-00-02-03

May 1, 2000

Box Provisional Patent Application
Assistant Commissioner for Patents
Washington, D. C. 20231

Enclosed herewith for filing is a patent application, as follows:

Inventor(s): Edward Nichols & Huntly F. Morrison

Title: A PERMANENT ELECTROMAGNETIC SYSTEM FOR MEASURING FORMATION
RESISTIVITY ADJACENT TO AND BETWEEN CASED WELLS

X Return Receipt Postcard
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17 Page(s) Specification (not including claims and coversheet)
2 Page(s) Claims
1 Page Abstract
8 Sheet(s) of Drawings (Informal)
0 Page(s) Declaration For Patent Application (signed)
0 Page(s) Recordation Form Cover Sheet for Assignment (in duplicate)
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0 Page(s) PTO Form 1449 citing 5 references
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Respectfully submitted,

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PROVISIONAL PATENT APPLICATION

5 A PERMANENT ELECTROMAGNETIC SYSTEM FOR
MEASURING FORMATION RESISTIVITY ADJACENT TO AND
BETWEEN CASED WELLS

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**A PERMANENT ELECTROMAGNETIC SYSTEM FOR
MEASURING FORMATION RESISTIVITY ADJACENT TO AND
BETWEEN CASED WELLS**

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BACKGROUND OF THE INVENTION

Geologic formations defining a reservoir for the accumulation of hydrocarbons in the subsurface of the earth contain a network of interconnected paths in which fluids are disposed that ingress or egress from the reservoir. To determine the behavior of the fluids in the aforementioned network, knowledge of both the porosity and permeability of the geologic formations is desired. From this information, efficient development and management of hydrocarbon reservoirs may be achieved. For example, the resistivity of geologic formations is a function of both porosity and permeability. Considering that hydrocarbons are electrically insulative and most formation water contains salts, resistivity measurements are a valuable tool to determine the presence of hydrocarbon reservoirs in geologic formations and to monitor the changes in hydrocarbon content as production of the hydrocarbon proceeds.

To that end, there have been many prior art attempts to determine the electrical resistivity of geologic formations surrounding and between boreholes drilled into the geologic formations of interest. In two articles, Crosshole electromagnetic tomography: A new technology for oil field characterization, The Leading Edge, March 1995, by Wilt et al. and Crosshole electromagnetic tomography: System design considerations and field results, Society of Exploration Geophysics, Vol. 60, No. 3, 1995 by Wilt et al., measurement of geologic formation resistivity is described employing a low frequency electromagnetic (em) system.

Fig. 1 shows the configuration of equipment used in the measurement of geologic formation resistivity between two boreholes. A transmitter, T, is located in one borehole and consists of a coil C_T having multi-turn horizontal loop (vertical solenoid) of N_T turns, having an effective cross section A_T . The multi-turn horizontal loop carries an alternating current, I_T , at a frequency of f_0 Hz. In free space this multi-turn horizontal loop produces a time varying magnetic field, B_0 . The magnetic field, B_0 , is proportional to the

magnetic moment of the transmitter, M_T , and to a geometric factor, k_1 . The magnetic moment of the transmitter M_T is defined as follows:

SS⁵²

$$(1) \quad M_T = N_T I_T A_T$$

5 The geometric factor, k_1 , is a function of a spatial location and orientation of a field component of the magnetic field, B_0 , measured by a receiver, R, with respect to the magnetic moment of the transmitter, M_T . The receiver is located spaced-apart from the transmitter, T, and typically disposed in a borehole in the earth. In free space, therefore, the magnetic field, B_0 , is defined as follows:

$$(2) \quad B_0 = k_1 M_T.$$

10 The receiver, R, typically includes a multi-turn loop of wire, i.e., a coil, C_R , having N_R turns of wire, wound about a core of high permeability metal or ferrite. The changing magnetic field B_R , sensed by the receiver, R, with frequency f_0 , creates an induced voltage V_R in the coil which is proportional to, B_R ; the frequency, f_0 ; the number of turns of wire, N_R ; the effective cross-sectional area of the coil, A_R ; and the effective permeability, μ_R , of the coil C_R . From the foregoing, it is shown that V_R is defined as follows:

$$(3) \quad V_R = f_0 B_R N_R A_R \mu_R$$

Simplifying equation (3) above, V_R may be written as follows:

$$(4) \quad V_R = k_R B_R$$

20 where $k_R = f_0 N_R A_R \mu_R$. The product of $A_R \mu_R$ is difficult to calculate. To accurately determine $A_R \mu_R$, C_R is calibrated in a known field, at a known frequency to find an exact value for k_R . Thereafter, the magnetic field, B_R , sensed by the receiver, R, is related directly to the measured voltage V_R by the following:

$$(5) \quad B_R = V_R / k_R$$

25 When this system is placed in a conducting geologic formation the time varying magnetic field, B_0 , produces an electromotive force in the geologic formation, which in turn drives currents therein, shown schematically as L_1 . The currents, L_1 , are

proportional to the conductivity of the geologic formation and are concentric about the longitudinal axis of the borehole. The magnetic field proximate to the borehole is a result of the free space field, B_0 , called the primary magnetic field, and the field from the current L_1 , called the secondary magnetic field.

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5 The current L_1 is typically out of phase with respect to the transmitter current I_T . At very low frequencies, where the inductive reactance of the surrounding formation is small, the induced current L_1 is proportional to dB/dt and is consequently 90° out of phase with respect to I_T . As the frequency increases, the inductive reactance increases and the phase increases to be greater than 90° .

10 The secondary magnetic field at the receiver, R , is caused by the induced current and consequently also has a phase shift and so the total field is complex. The total measured field has a component, B_R , in-phase with the transmitter current I_T , (called the real component) and a component, B_L , phase shifted by 90° (called the imaginary or quadrature component). The values of the real, B_R , and quadrature components, B_L , of the
15 magnetic field at a given frequency and geometrical configuration uniquely specify the electrical resistivity of a homogenous formation pierced by the drill holes. In an inhomogeneous geologic formation, the complex field is measured at a succession of points along the longitudinal axis of the receiver borehole for each of a succession of transmitter locations. The multiplicity of T-R locations suffices to determine the
20 inhomogeneous resistivity between the holes as described in the papers above.

In general, the inhomogeneous distribution of electrical resistivity is determined through a process called inversion which is well described by Audio-frequency electromagnetic tomography in 2-D, Geophysics, Vol. 58, No. 4, 1993 by Zhou et al., Electromagnetic conductivity imaging with an iterative born inversion, IHERE
25 Transactions on Geoscience and Remote Sensing, Vol. 31, No. 4, 1993 by Alumbaugh et al., An approach to nonlinear inversion with applications to cross-well EM tomography, 63rd Annual International Meeting, Society of Exploration Geophysics, Expanded Abstracts, 1993 by Torres-Verdin et al., and Crosswell electromagnetic inversion using integral and differential equations, Geophysics, Vol. 60, No. 3, 1995 by Newman. This
30 process has been well demonstrated for the determination of resistivity in the vicinity of a single borehole or between spaced-apart boreholes walls and is described in detail by Crosswell electromagnetic tomography: System design considerations and field results.

Geophysics, Vol. 60, No. 3, 1995 by Wilt et al., Theoretical and practical considerations for crosswell electromagnetic tomography assuming a cylindrical geometry, Geophysics, Vol. 60, No. 3, by Alumbaugh and Wilt, and 3D EM imaging from a single borehole: a numerical feasibility study, 1998 by Alumbaugh and Wilt.

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5 In brief, one embodiment of the inversion process consists in assigning resistivities to a multitude of cells or elements of the volume surrounding, or between, boreholes. The resistivities are systematically varied until, in a least squares sense, the results from the cellular model of the formation match the observed data taken with the field transmitter receiver system described herein. In another embodiment, a more
10 specific model of the formation is assumed using geological, well log or other geophysical data. The parameters of this model (e.g. resistivity distribution, shape, layer thickness, etc.) are varied until, again in a least squares sense, the numerical results from the model match the field results. In another embodiment direct images of the distribution of resistivity may be obtained following the principles of diffusion
15 tomography as described by Audio-frequency electromagnetic tomography in 2-D, Geophysics, Vol. 58, No. 4, 1993 by Zhou et al. In yet another method multifrequency em data is transformed to a mathematically defined wave field domain and the data are processed following the procedures of seismic tomography. These means of interpreting the em data are included here to illustrate the fact that em methods are of practical use in
20 determining the resistivity of geological formations.

The measurements are usually made before extraction of hydrocarbons takes place and during the extraction process. To that end, the system of Fig. 1 is principally directed to detecting hydrocarbon reservoirs and to monitoring the changes in reservoir resistivity as hydrocarbon is withdrawn in an uncased borehole. Boreholes are,
25 however, typically cased with conductive liners (also called casings) in order to preserve the physical integrity of the boreholes during subsequent hydrocarbon extraction. A problem exists in that the conductive liners are electrically conductive and are themselves inhomogeneous and strongly attenuate the ac magnetic field introduced into the formation. They are very difficult and costly to remove from the borehole once installed. As a result,
30 the system shown above in Fig. 1 does not facilitate analysis of a hydrocarbon reservoir once conductive liners are installed and extraction of the hydrocarbons begins.

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The problems presented by conductive liners are described by Augustin et al., in A Theoretical Study of Surface-To-Borehole Electromagnetic Logging in Cased Holes, Geophysics Vol. 54, No. 1 (1989); Uchida et al., in Effect of A Steel Casing on Crosshole EM Measurements, SEG Annual Meeting, Texas (1991); and Wu et al. in Influence of Steel Casing on Electromagnetic Signals, Geophysics, Vol. 59, No. 3 (1994). From these papers, it is seen that the conductivity may be modeled as an additional shorted wire closely coupled to the transmitter T, shown schematically as L_2 in Figure 1.

The net or effective magnetic moment, M_{eff} , of the transmitter, T, conductive liner combination is dictated by the inductive coupling therebetween. Physically, the resistivity of the conductive liner is very low and the inductance relatively high. This results in a current being induced in the conductive liner that is approximately 180° out of phase of the transmitter current I_T , i.e., the induced current is of opposite polarity to the transmitter current, I_T , but almost of the same moment. In this manner, the magnetic field external to the conductive liner is greatly reduced. In effect, the conductive liner "shields" the transmitter, T, from the receiver, R, positioned outside of the conductive liner. The external field is produced by the difference in current, and hence moment, in the transmitter and conductive liner.

Since the induced moment in the liner is large, and nearly equal to the transmitter moment, small changes in the properties of the liner produce large fractional changes in the net of effective moment. In practice, liners are known to be inhomogeneous: there are variations in liner radius, thickness, permeability, and conductivity caused either by manufacturing/processing procedures or by corrosion/stress/temperature processes after installation. The central problems for the em methods described above for non-cased, or open, well surveys is that the fields from the transmitter are severely attenuated in a cased well and that the net moment is highly variable as the transmitter traverses the length of the well. Without knowing the casing properties very precisely, it is difficult to distinguish between external field variations caused by the liner and the formation.

An analogous situation affects a magnetic field sensor within a cased borehole. The field to be detected induces currents concentric with the receiver coil whose sense is such as to reduce the field within the liner. The field to be detected is consequently highly attenuated and the measurement is highly influenced by the

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variations in attenuation caused by the variation in liner properties, an example of which is graphically demonstrated by the slope of curve 10 shown in Fig. 2. Often, the design criteria for a crosshole survey of a cased borehole reduces the signal to a level that is undetectable by standard receivers. Moreover, the variance in conductivity, permeability, and thickness along a longitudinal axis of a liner makes difficult determining the attenuation factor at any given point. This has been said to cause errors in the field measurements that are not easily corrected.

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One prior art attempt to overcome this problem involved inclusion of a separate small-scale transmitter-receiver within the cased borehole to accurately measure the casing properties. The measured casing properties would then be used to correct the measured crosshole data. See Lee et al., Electromagnetic Method For Analyzing The Property of Steel Casing, Lawrence Berkeley National Laboratories report 41525, February 1998.

Another prior art attempt to correct for the attenuation of a liner involved positioning of a monitor receiver adjacent to the transmitter in the cased borehole. In this manner, an attempt is made to predict the attenuation sensed by the external receiver that is disclosed in United States patent application number 09/290,156, filed April 12, 1999, entitled Method and Apparatus for Measuring Characteristics of Geologic Formations, having Ugo Conti listed as inventor.

A drawback with the aforementioned prior art attempts to correct for the attenuation factor concerns the implementation of auxiliary transmitters or receivers that increases the cost of a system and its complexity. Further, there is limited empirical evidence to suggest that the added cost and complexity of these systems is justified. It is not yet known whether these systems may accurately correct for the attenuation factor.

In United States patent application number 09/394,852 filed September 13, 1999, entitled An Electromagnetic Induction Method and Apparatus For The Measurement of the Electrical Resistivity of Geologic Formations Surrounding Boreholes Cased with A conductive Liner, and having Huntly F. Morrison and Edward Nichols a method for measuring formation resistivity adjacent to and between cased wells using low frequency (<200Hz) multiturn solenoidal coils within cased wells is disclosed. Specifically, the invention allows measuring the resistivity of geologic formations in

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which a borehole has been formed therein and encased with a conductive, or metallic, liner made from materials such as steel. This has been achieved by providing a method and computer program product that attenuates, if not removes, the effects of the metallic liner by taking appropriate ratios of measured fields, either inside or outside of the metallic liner. In this manner, attenuation due to the casing is practically canceled.

A limitation with the invention disclosed by Morrison and Nichols is that once production from the well has begun, production tubing is run from the surface to the producing zone. The production tubing leaves no room for the em system to move in the well. Repeated measurements to monitor production or enhanced recovery processes then require repeated removal and reinsertion of the production tubing. This is a costly operation and it is clear that a permanent monitoring system, on the outside of the casing, would be more cost effective.

What is needed, therefore, is a cross-well measurement technique that provides accurate measurements of geologic formations without requiring detailed information concerning the properties of a liner casing the same and does not reduce production efficiency of a borehole.

SUMMARY OF THE INVENTION

Provided is an apparatus to measure characteristics of geologic formations, such as hydrocarbon reservoirs, that feature attaching a plurality of spaced-apart transmitter-receiver units on an exterior surface of a single casing lining a borehole. The individual transmitters and receivers are connected to transmit signals to a surface mounted processing system via cable connected to the exterior surface.

Were cross-well measurements desired to occur between adjacent boreholes, in an alternative embodiment transmitter units may be mounted to the exterior surface a casing in one borehole. Receiver units are mounted to the exterior surface of a casing lining an adjacent borehole. For cross well measurements the transmitters would be deployed in one well and the receivers in another. In practice both single well and cross well measurements may be employed for maximum resolution of the formation. With the invention described herein the transmitters and receivers can also be spaced on the same scale as used in open hole induction logging apparatus. The transmitters and

receivers may be placed at depths of interest to reservoir monitoring, i.e. within and straddling the reservoir.

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These and other embodiments of the present invention along with many of its advantages and features are described in more detail in conjunction with the text below and attached figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a simplified plan view of a prior art cross-well electromagnetic measurement system;

Fig. 2 is a perspective view of a geologic formation undergoing crosswell electromagnetic analysis;

Fig. 3 is a simplified plan view of a cross-well electromagnetic measurement system in accordance with the present invention;

Fig. 4 is a simplified plan view showing the configuration of a solenoid employed to obtain empirical data employing the present invention;

Fig. 5 is a graphical representation of the empirical data obtained using the configuration shown above in Fig. 4;

Fig. 6 is a simplified plan view showing a cross-sectional area of a solenoid, in accordance with the present invention, and the orientation of the electromagnetic fields and current generated by the solenoid;

Fig. 7a-d show a graphical representation the empirical data obtained using the configuration shown above in Fig. 4; and

Fig. 8 is a graphical representation showing a comparison of response information for solenoids, such as the one discussed above with respect to Fig. 4, having different configurations.

DESCRIPTION OF THE SPECIFIC EMBODIMENTS

Referring to Fig. 2, a geologic formation 11 under analysis includes one or more boreholes, shown generally as 12a and 12b and a reservoir of resources of interests,

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consisting of a solenoid wound on the casing is the counter moment caused by the current induced in the casing. This counter moment can be reduced by cutting thin axial slots (one may be sufficient) in the casing to interrupt the induced current flow. This process is equivalent to the use of thin insulated strips used in the core material of a normal solenoidal receiver. Slotted casing is already used in oil field applications to allow ingress of formation fluids at levels of interest. Such a transmitter or receiver could consequently be wound on essentially standard casing.

The moments achievable with such a transmitter or the sensitivities achievable in a receiver solenoid wound on the casing are comparable to or larger than the effective moments achieved with solenoids wound on high mu material located within the casing. This is due to the greater radius and length that is conveniently available with a casing core.

Slotting the casing does not cancel all the circulating counter current induced in the casing in the vicinity of the windings. While a slot of the same length as the winding interrupts the current within the length of casing under the winding the induced currents are forced to circulate in the casing off the ends of the winding. In this region the currents depend on the geometric fall off of the inducing field of the solenoid and on the flux gathering effect of the casing permeability (which is not affected by the slot). Ideally one would like to introduce a magnetically insulating gap (a cylindrical segment of zero relative permeability) at each end of the winding to reduce the magnetic flux threading the adjacent casing.

We have found that for frequencies useful for single well or cross-well conductivity imaging on the reservoir scale (10s to 100s of meters) a solenoid wound directly on standard casing with a single slot extending a meter or so beyond the winding has more than adequate moment for a permanent monitoring system. Furthermore we have found that such slots permit the use of frequencies as high as 10,000Hz with only modest attenuation which permits the use of 'standard' high resolution induction logging in the presence of casing.

Experimental data was obtained employing the present invention by examining the fields produced by a solenoid on a typical steel casing. The solenoid consisted of 100 turns wound on either the steel casing or on a plastic pipe of the same

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radiua. The configuration of the solenoid and the dimensions are shown Fig. 4. Fields were measured with a standard magnetic field sensor manufactured by Electromagnetic Instruments Inc. (model BF-6), the frequency of the current in the solenoid was varied from 1.0Hz to 10,000Hz. The current itself was measured at each frequency, and the measured field was normalized by this current.

The results are presented as the ratio of the field measured with the casing to the field measured with no casing present, a direct experimental determination of the effective permeability of the casing core. This ratio is plotted in Fig. 5. The magnetization enhancement causes an effective increase in the moment at dc and the induced currents cause a decrease as the frequency increases. The enhancement of the field due to the magnetization of the casing is evident for frequencies below about 1000Hz.

The measurements were made with two slot lengths. The first, indicated by 'short slot' on Figs. 4 and 5, extended about 2 casing diameters past the end of the winding and the second, 'long slot' extended about 7 casing diameters past the end. The attenuation for the non-slotted casing falls-off below a few hundred Hz as predicted by induction theory. Above a few hundred Hz the current is confined to the outer section of the casing by skin depth effects and the magnitude of the counter current is reduced. The slots clearly interrupt the induction current attenuation essentially independent of slot length up to about 300 Hz above which the long slot is more effective than the short. At the maximum frequency of interest for reservoir imaging, say 500 Hz, the field is only attenuated by at most a factor of 3.5 for the short slot compared to a factor of 10 for the unslotted casing.

It should be noted that the attenuation factors increase very little for the long slot as the frequency increases to 10,000Hz (10kHz) whereas the field for the unslotted casing has been attenuated by a factor of almost 50 at this frequency. This implies that formation resistivity monitoring can be done with casing wound solenoids at the same resolution as is achieved with open hole induction logging.

The strength of the magnetic field is proportional to the moment, M , of the transmitter, which is given by

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$$(6) \quad M = \kappa_r \mu_0 N I A$$

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where μ_0 is the magnetic permeability of the free space, κ_r is the relative permeability, A is the cross sectional area of the solenoid, I is the current and N is the number of turns. In free space at a distance R away perpendicular to the axis of the solenoid the magnetic field produced is given by

$$(7) \quad B_{ax}(\text{Tesla}(T)) = (\mu_0 / 4\pi) (\pi a^2) N I / R^3$$

where a is the radius of the solenoid, an example of which is shown in Fig. 6.

10 In practical units of nT (10^{-9} T). The field at a distance R away is

$$(8) \quad B_{ax} = 100 N I A / R^3$$

15 As the transmitter current is made to vary sinusoidally with a frequency f (Hertz, Hz), the associated changing magnetic fields induce current in the conducting formation and in any nearby conductors such as the drill rod or casing. These currents dissipate energy and the fields are attenuated over and above the dc attenuation. Fundamentally, then, the overall attenuation must always increase as the frequency of the transmitter increase.

20 The amplitude of the fields produced within the formation, including along the drill hole, at points distant from the transmitter, can be calculated as a function of the formation resistivity and frequency. Anticipating that compromises may be required between frequency and range, responses have been calculated for several frequencies between 30Hz and 1000Hz. These response plots are presented in Fig. 7. The field strength in nanoTeslas (nT, 10^{-9} T), is for a unit moment in the transmitter. Using these plots it is a straightforward exercise to develop a general, or example, design of a

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realizable system. The analysis below is for one typical design and not for the optimum design: it is presented to show the feasibility of the new system. The system design for the maximum range for frequencies of interest now depends on the maximum sensitivity achievable in the receivers and the maximum practical moment in the transmitter. We
5 consider the receiver first.

The receiver, in accordance with the present invention includes multiturn solenoid wound around the casing. Enhancement of the received field due to magnetization and attenuation due to the induction currents, affect the receiver in exactly the same way as the transmitter. The receiver essentially acts like a solenoid with an
10 effective given by Fig. 5. From Faraday's Law, the voltage across the terminals of the solenoid in an axial field of B Teslas is given by:

$$(9) \quad V = N\kappa_m A \delta B / \delta t = \kappa_m 2\pi f N A B$$

15 where A is the cross sectional area of the solenoid and N the number of turns.

For this sample design we have chosen a casing of 10cm. radius so $A = \pi 10^{-3} m^2$. The frequency is then set to 100Hz which is representative of frequencies used in cross borehole applications. With a κ_m of about 6.4, shown in Fig. 5, and with these values of A and f the voltage is defined as follows:

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$$(10) \quad V = \kappa_m \times 2\pi \times f \times N \times \pi 10^{-3} \times B.$$

This design is similar to that used in standard high sensitivity industrial coil receivers. In these systems the core is high permeability metal in the form of
25 insulated strips to optimize the magnetization properties of the core while preventing the induction image currents. Our practical experience with these receivers shows that the

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minimum detectable voltage is about 10nV (10^{-8} V). From (10) the minimum detectable field is, therefore, determined as follows:

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$$(11) \quad B = \frac{10^{-8}}{\kappa_m \times 2\pi \times f \times N \times \pi 10^{-3}} \approx \frac{5 \times 10^{-8}}{\kappa_m f N}.$$

5

Again from practical experience it is known that up to tens of thousands of turns can be used, apparently yielding very low equivalent fields. For example with 10,000 turns and a frequency of 100 Hz and a κ_m of 6.4, shown in Fig. 5, the magnetic field sensitivity would be 0.78×10^{-14} T or approximately 10^{-5} nT.

10

Because the current in the transmitter solenoid dissipates power, an optimum transmitter would achieve the highest moment with the minimum power. As an example of a practical design we assumed a single layer of windings on a 1m length of casing (again of 10cm radius). Once the number of turns is chosen the wire diameter and its total resistance (R) and inductance (L) is fixed. The inductance is important because the voltage needed to drive the desired current depends on the product fL and as a practical matter it is also desirable to keep this drive voltage low.

15

A summary of the design information for such a transmitter is contained in the plots of Fig. 8. Here the axes are the number of turns (N) and the current in the solenoid, I, and the resulting moment M and power dissipation (required from the power supply). It is quickly seen that the optimum transmitter consists of the smallest number of turns with the largest wire. It is also seen that a moment of 150 is quite feasible with a little over 300 turns, 12Amperes and a power dissipation of only 30 Watts. Such a transmitter would have an operating voltage of 50 at 100 Hz. These results were obtained for an air core coil. Wound on the casing the moment would be increased by κ_m or by 6.4 at 100 Hz yielding a moment of about 1000.

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The above design is intended to be illustrative and non-conclusive. Farther optimization could be achieved with the following changes to the basic design (all of which are possible embodiments of this invention. The solenoid could be longer with

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corresponding higher moment and sensitivity. In a practical system the current may be limited by the power supply. In this case the number of turns on the transmitter can be increased by winding more layers of turns. Farther increasing wire size with more turns can keep the power dissipation the same while increasing the moment.

5 For the purpose of this illustrative design we can thus assume that a moment of 1000 can readily be achieved at 100 Hz. Increasing the frequency to 500 Hz decreases the moment by only 25% while increasing the operating voltage to only 250 volts. It is clear that much higher frequencies may be employed using the externally wound solenoids than with the present solenoids mounted within the casing. Although
10 the latter employ moments as high as 1000 the field is effectively reduced to zero by 500 Hz.

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15 In this design example we next have to consider signal to noise - basically we have to provide a signal that is well above the sensitivity or noise level of the receiver. In our discussion of the receiver above we determined that a conservative detection threshold was 10^{-3} nT. If we wish to make a measurement accurate to 1.0% we must provide a field of at least 10^{-3} nT or we must signal average over a long enough time to reduce the receiver noise by a factor of 100. We now discover another important advantage of the solenoids wound on the casing and permanently emplaced. There is really no limit on the time that the signals can be averaged. In all the cased hole and open
20 hole applications of this technology the transmitters and receivers are typically moved along the axis of the bore hole in a short time because production has been interrupted to conduct the survey or, in new wells, there is urgency in completing the survey so as to install the casing as quickly as possible. At 100 Hz existing borehole systems average for about one second. In the permanently mounted systems averaging could be extended to
25 10,000 seconds, about 3 hours, with a corresponding increase of 100 in signal to noise. This basically means that the desired signal level can be placed at the intrinsic sensitivity of the receiver, namely 10^{-3} nT.

The range can now be determined from Fig. 7 by simply drawing a horizontal line on each plot at a field strength of 10^{-3} nT after multiplying the amplitude
30 scale by the moment, in this case 1000. This is equivalent to drawing the line on the plots for a moment of one at an amplitude of 10^{-3} . The increase in range compared to the placement of the transmitters and receivers inside the casing is significant, especially at

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frequencies above 100 Hz. For the most conductive ground, 1 ohm m, the range at 100 Hz is almost 500m; at 5 ohm m it has increased to 800m. More importantly for the inversion process where the use of a spectrum of frequencies improves the resolution, much higher frequencies can be used. For example in a typical sandstone reservoir of 10 ohm m resistivity the range is 500m or above for all frequencies up to 1000Hz.

The design diagrams of Fig. 7 reveal many other variants of crosswell and single well resistivity mapping systems in cased boreholes that have not heretofore been possible or described. For example, in high resistivity formations such as carbonates excellent resolution of small scale features such as fracture zones can now be achieved using frequencies as high as 10,000Hz. Note that as the resistivity goes up the formation attenuation goes down and lower moments may be used. This automatically reduces the voltage required on the transmitter to practical levels.

In single wells arrays of transmitters and receivers spaced as closely as a meter, using solenoids of small length and very small moment can be used in configurations similar to those used now in conventional deep induction logging. The radius of investigation of these systems could range from a few meters to as much as 50-100m depending on the formation resistivity.

In a multiwell field the receivers in the permanently mounted solenoids could receive signal from a transmitter placed near the drill bit in a new fill-in hole in the oil field. This arrangement would serve two important purposes. First, it could be used to monitor the formation resistivity in the formation being drilled as the drilling proceeds, referred to as logging while drilling. Secondly, it could be used to telemeter data about the conditions of the drill bit itself or auxiliary logging data from the vicinity of the drill bit to the surface via the nearby well. The bandwidth for such a telemetry system is much higher than any system now used to send information from the drill bit to the surface. Details for a transmitter attached to the drill string behind the drill bit and for the bandwidth of the telemetry may be found in the aforementioned patent application having Morrison and Nichols listed as inventors, which is incorporated by reference in its entirety.

For practical implementation of the new invention one embodiment is to have a relatively simple cable configuration service any number of transmitters or

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receivers via the use of 'smart relays' at each solenoid. The electronics associated with each solenoid has an address. A two-wire control line sends coded signals which activate switches and electronics at a desired solenoid, open circuiting others in the array. Power is conveyed by direct current in one heavy gauge line, the ground or return path being
5 provided by the casing itself.

For a transmitter the control line selects the desired transmitter connecting the power to the transmitter electronics and thereafter supplying the frequency and timing to control the transmitter for the duration of the measurement. A second pair of wires conveys a measure of the actual transmitter current to the surface.

10 For a receiver the first pair of control lines selects the desired unit and connects power to its electronics and the second pair conveys the measured solenoid output to the surface. Such a permanently installed system would be simple and robust. High quality 'military specification' components are available that will provide long life even in harsh conditions. The actual circuits used in the transmitter and receiver have been
15 developed and field tested and proven in the existing crosswell systems described in the patent applications of Morrison and Nichols.

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20 Since casing has to be inserted through previously installed casing there are severe limits on the thickness of the windings and electronics. The typical clearance, say between 13 3/8 casing and the next lower size, 9 5/8 in, is only 2 3/4 in diameter or 1 3/8 in radius. Practically this means only 1 in radius for the coils, electronics, and protective shell. This is sufficient for the coils and, given the virtually limitless length, perfectly adequate for the electronics. For the final and smallest diameter casing there is only half an inch of radius requiring a custom made thin cylindrical electronics package.

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WHAT IS CLAIMED IS:

1 1. A method for measuring characteristics of a geologic formation
2 employing metallic casings to be disposed in boreholes formed in said geologic formation,
3 said method comprising:
4 mounting a transmitter and a receiver to one of said metallic casings;
5 disposing said one of said metallic casings into said boreholes;
6 producing, within a first area of said geologic formation, a first magnetic field;
7 sensing, within a second area of said geologic formation, a second magnetic
8 field; and
9 measuring said characteristics as a function of said second magnetic field.

1 2. The method as recited in claim 1 further including mounting additional
2 transmitters to said one of said metallic casings.

1 3. The method as recited in claim 1 further including mounting additional
2 receivers to said one of said metallic casings.

1 4. The method as recited in claim 1 further including forming a slot in
2 said one of said metallic lines that extends from an exterior surface of said metallic casing to
3 an interior surface thereon.

1 5. The method as recited in claim 1 wherein said one of said metallic
2 casings having said transmitter mounted thereto is disposed in a borehole that differs from the
3 borehole in which said one of said metallic liners, on which said receiver is mounted, is
4 disposed.

1 6. The method as recited in claim 1 wherein said transmitter and said
2 receiver are mounted to a common metallic casing.

1 7. An apparatus for measuring characteristics of a geologic formation,
2 that has boreholes formed therein with metallic casings disposed within said boreholes, said
3 apparatus comprising:
4 a transmitter;

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5 a receiver, with said transmitter and receiver each being mounted to one of
6 said metallic casings;
7 a signal generator in data communication with said transmitter,
8 a processor in data communication with both said transmitter and said
9 receiver; and
10 a memory in data communication with said processor, said memory including
11 code to produce, in a first area of said geologic formation with said transmitter, a first
12 magnetic field; code to sense, within a second area of said geologic formation with said
13 receiver, a second magnetic field; and code to measure said characteristics as a function of
14 said second magnetic field.

1 8. The apparatus as recited in claim 7 further including additional
2 transmitters mounted to said one of said metallic casings, defining a plurality of spaced-apart
3 transmitters.

1 9. The apparatus as recited in claim 7 further including additional
2 receivers mounted to said one of said metallic casings, defining a plurality of spaced-apart
3 receivers.

1 10. The apparatus as recited in claim 7 wherein said one of said metallic
2 casings has interior and exterior surfaces and a slot formed therein extending between said
3 interior and exterior surfaces.

1 11. The apparatus as recited in claim 7 wherein said one of said metallic
2 casings having said transmitter mounted thereto is disposed in a borehole that differs from the
3 borehole in which said one of said metallic liners, on which said receiver is mounted, is
4 disposed.

1 12. The apparatus as recited in claim 7 wherein said transmitter and said
2 receiver are mounted to a common metallic casing.

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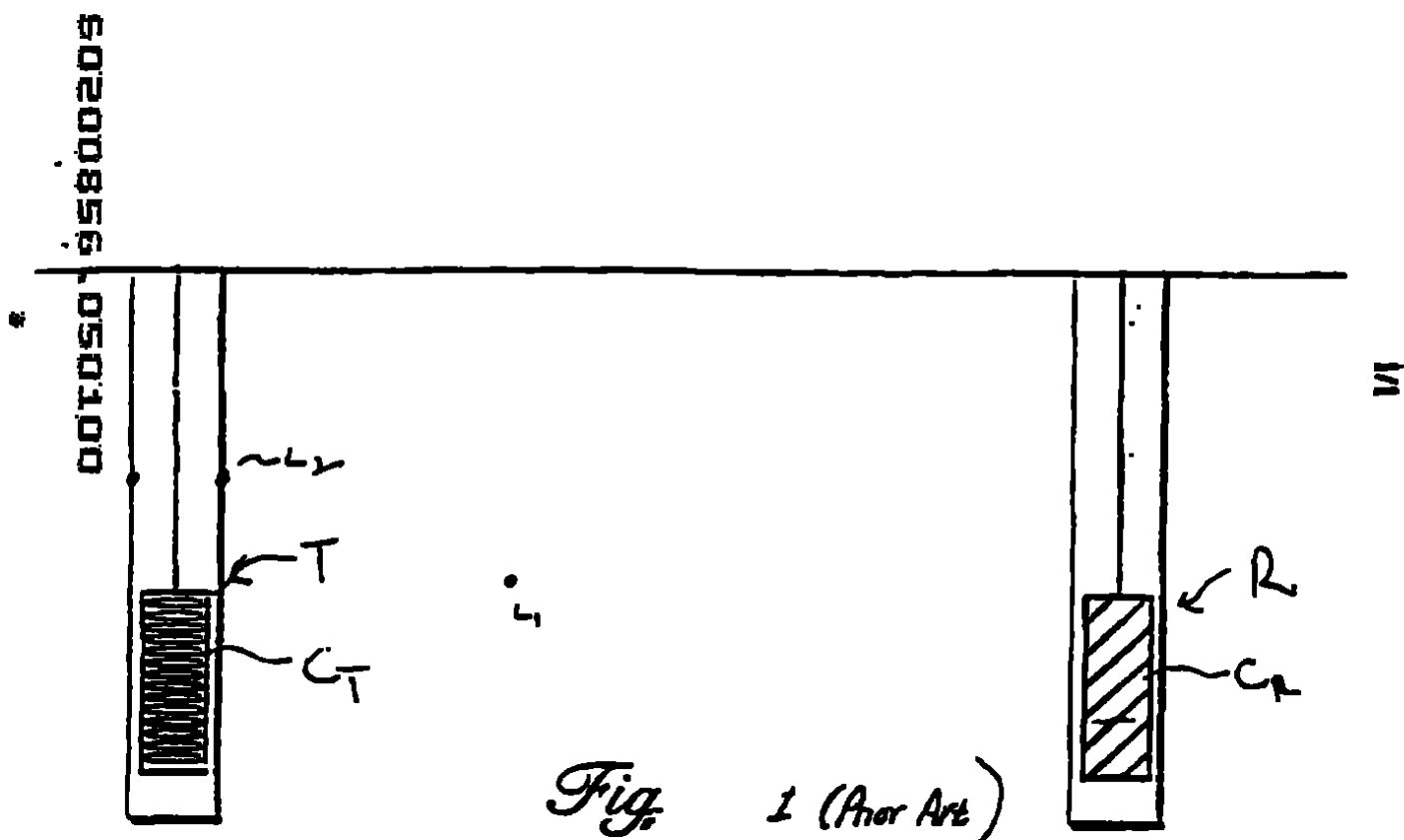
**A PERMANENT ELECTROMAGNETIC SYSTEM FOR MEASURING
FORMATION RESISTIVITY ADJACENT TO AND BETWEEN CASED
WELLS**

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ABSTRACT OF THE DISCLOSURE

5 Provided are a method and an apparatus to measure characteristics of a
geologic formation, such as hydrocarbon reservoirs, that feature attaching a plurality of
spaced-apart transmitter-receiver units on an exterior surface of a single metallic casing that
lines a borehole. The individual transmitters and receivers are connected to transmit signals
to a surface mounted processing system via cable connected to the exterior surface. Slots
10 may be formed in the metallic casing to enhance signal propagation therethrough.

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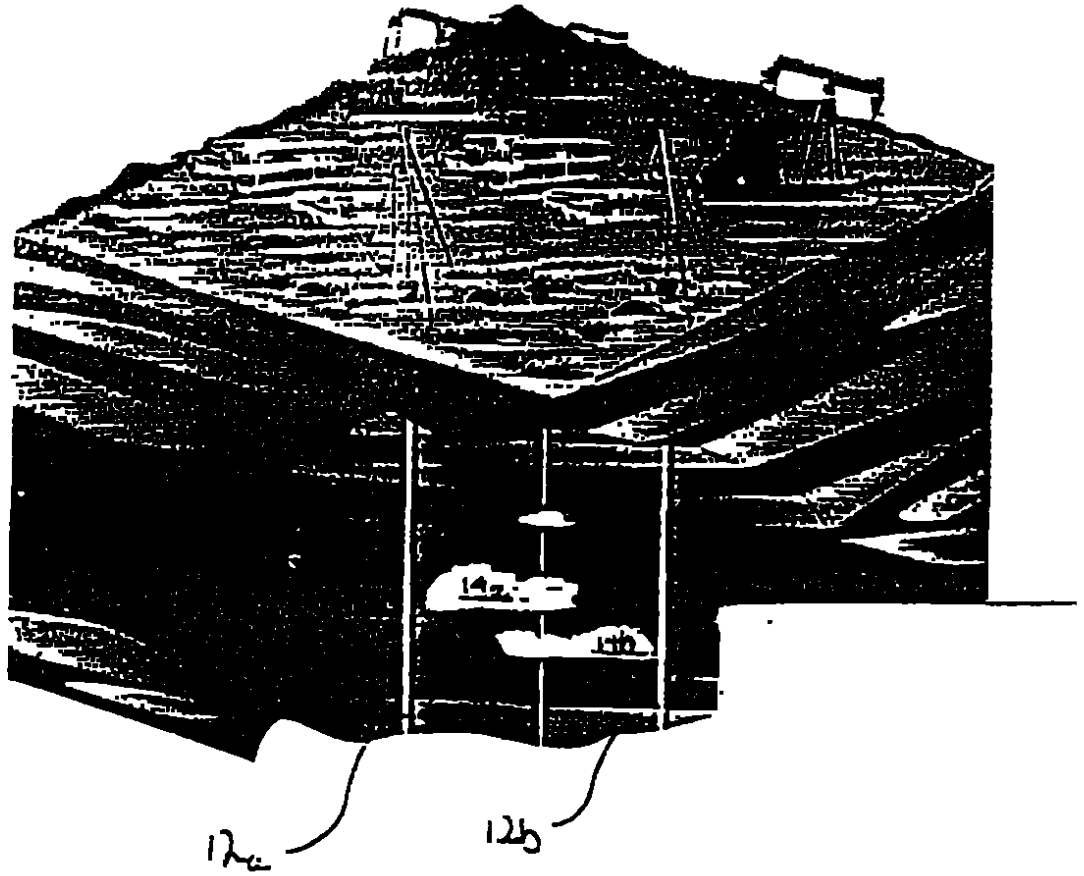


FIG. 2

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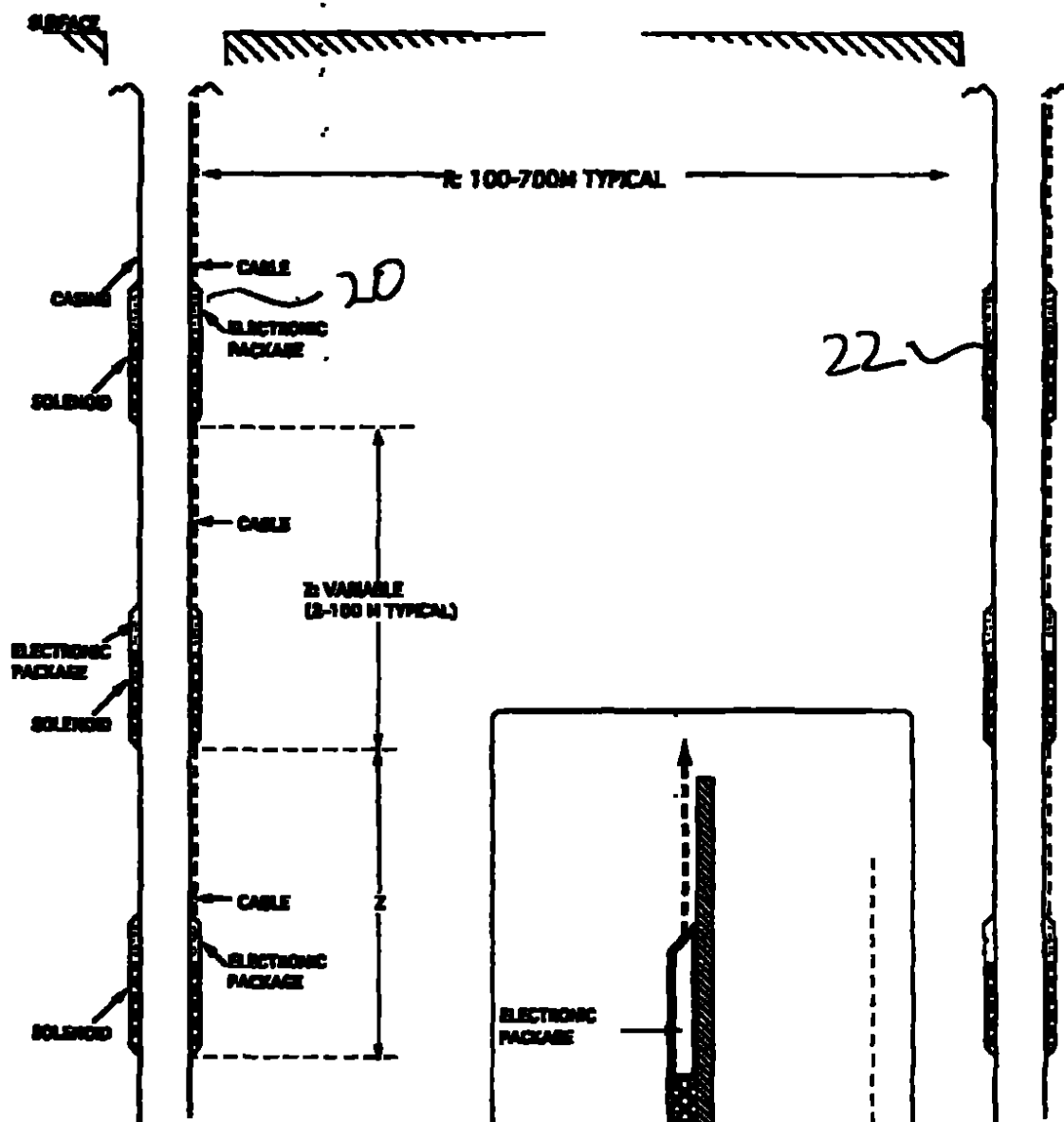
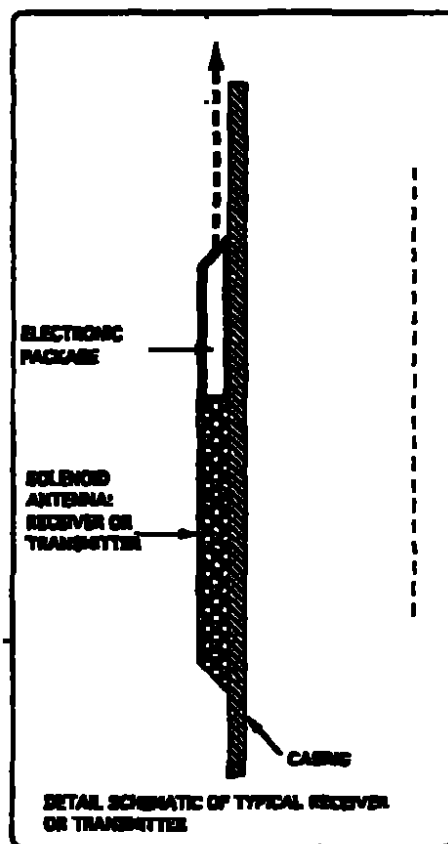


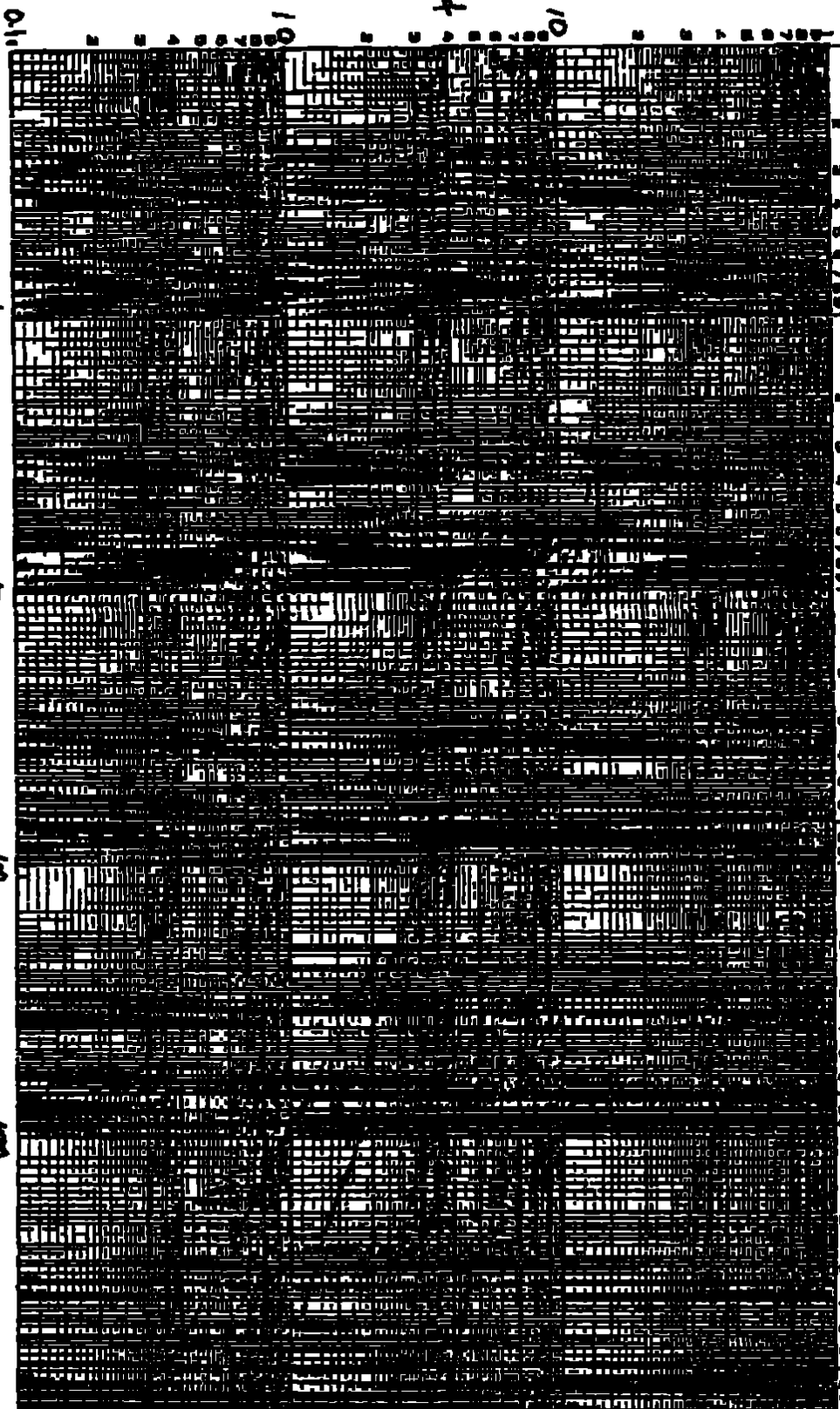
FIG. 3



CONFIDENTIAL



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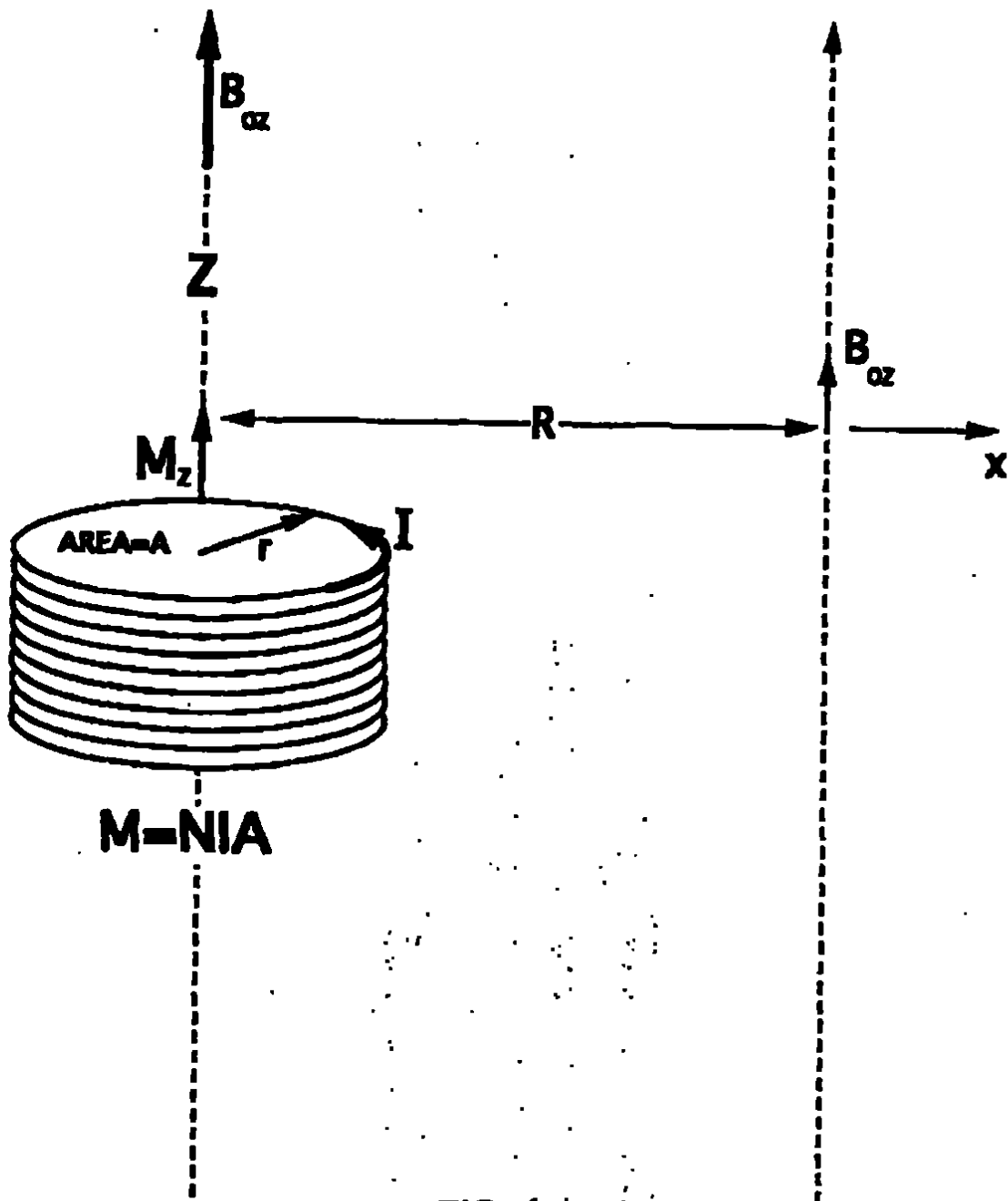


FIG. 6

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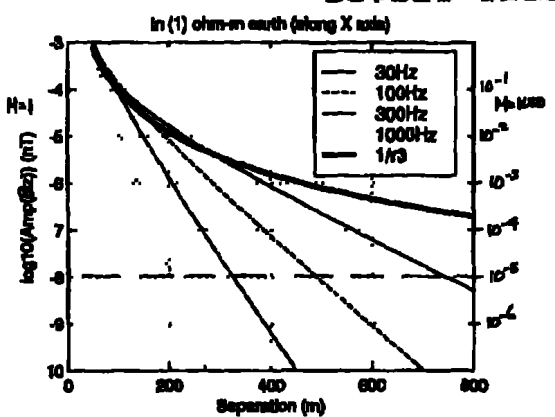


FIG. 7a

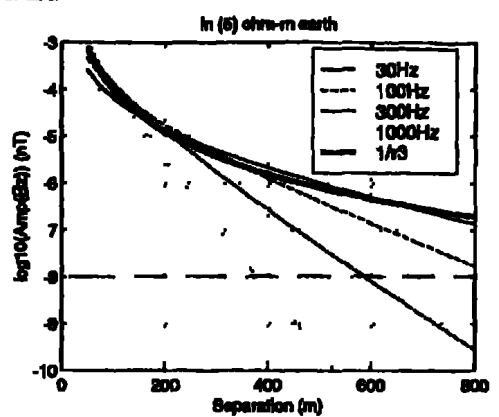


FIG. 7b

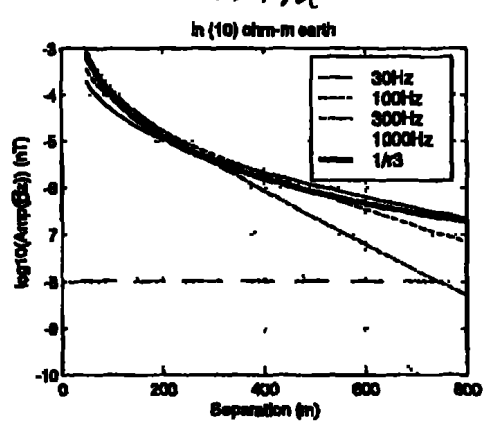


FIG. 7c

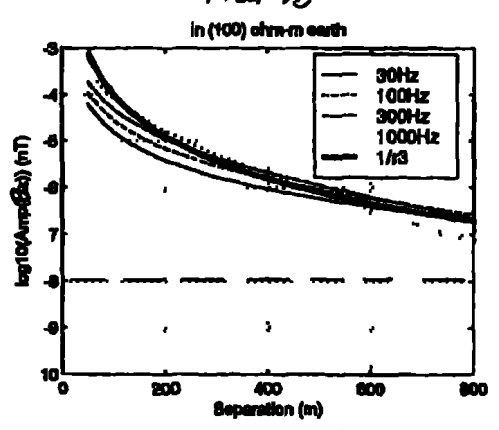
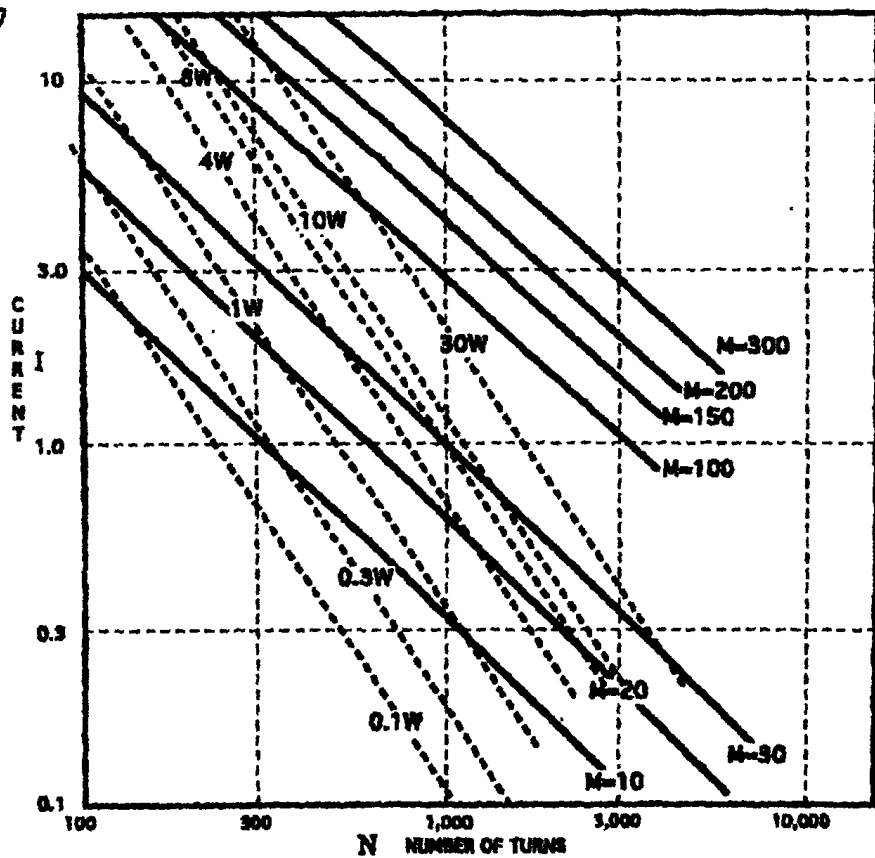


FIG. 7d

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FIG. 8

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