(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
23 March 2017 (23.03.2017)

WIPO | PCT

(10) International Publication Number
WO 2017/048263 A1

(51) International Patent Classification:
E21B 47/00 (2006.01) *G01V 3/38* (2006.01) *G01V 3/18* (2006.01)

(21) International Application Number:
PCT/US2015/050763

(22) International Filing Date:
17 September 2015 (17.09.2015)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 3000 N. Sam Houston Parkway E., Houston, TX 77032-3219 (US).

(72) Inventors: **SAN MARTIN, Luis, Emilio**; 306 South Gate Stone, Houston, TX 77007 (US). **KHALAJ AMINEH, Reza**; 4202 Island Hills Drive, Houston, TX 77059 (US). **DONDERICI, Burkay**; 3121 Buffalo Speedway #8305, Houston, TX 77098 (US).

(74) Agents: **CHHEDA, Tim, D.** et al.; Krueger Iselin LLP, P.O. Box 1906, Cypress, TX 77410-1906 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK,

[Continued on next page]

(54) Title: DETERMINING PERMEABLILITY BASED ON COLLAR RESPONSES

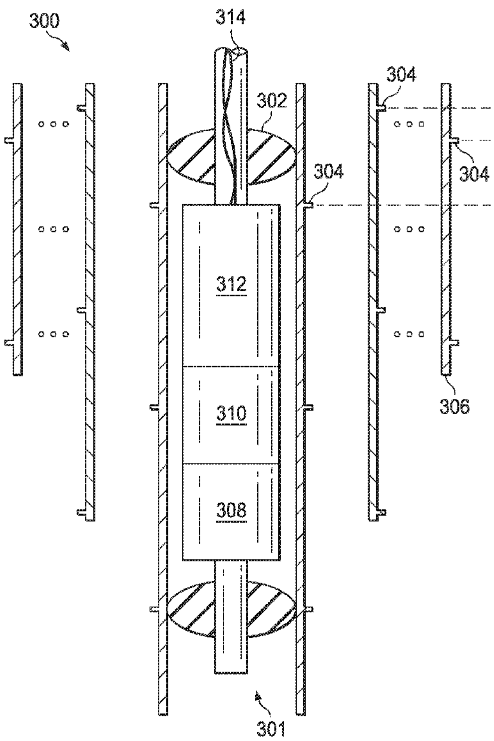


FIG. 3

(57) Abstract: A method for determining tubing permeability includes conveying a tool through a tubular string in a borehole. The tool includes a transmitter that transmits a primary electromagnetic field and a receiver that receives at least one collar response. The collar response includes a secondary electromagnetic field produced in response to the primary field by a collar in the tubular string. The method further includes determining a permeability of at least one portion of the tubular string based on a magnitude of the at least one collar response. The method further includes displaying a representation of the at least one portion of the tubular string based on the permeability.

WO 2017/048263 A1

SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

DETERMINING PERMEABILITY BASED ON COLLAR RESPONSES

Background

Scaling, corrosion, precipitates, and material defects are some problems faced by the oil and gas industry when managing production well and pipeline assets. These problems lead to diminished production in wells, casing integrity failure, and pipeline integrity failure any of which may result in costly and complex remediation measures. As such, electromagnetic techniques are commonly used to monitor the condition of the production and intermediate casing strings, tubing, collars, filters, packers, and perforations.

One electromagnetic technique is the eddy current technique. In this technique, when a transmitter coil emits the primary electromagnetic field, or signal, eddy currents are produced in, e.g., the casing. These eddy currents then produce secondary fields, or signals, which are received by a receiver coil. When recorded and processed, this data can be employed to perform an evaluation of the casing.

However, the geometry of concentric casing strings, studded with collars at different depths, makes it difficult to process the received signals. A collar is a threaded tubular section used to connect two sections of casing. Thus, the casing string has larger thickness at each collar section. As such, the sections of casing surrounded by collars are typically ignored in the eddy current technique in favor of using the more homogenous non-collar sections of the casing string. However, such exclusion results in an incomplete set of data on which to base decisions.

Brief Description of the Drawings

Accordingly, determining permeability based on collar responses is disclosed herein. In the following detailed description of the various disclosed embodiments, reference will be made to the accompanying drawings in which:

Figure 1 is a contextual view of an illustrative production environment;

Figure 2 is contextual view of an illustrative wireline embodiment;

Figure 3 is a functional schematic view of an illustrative tool for determining permeability based on collar responses;

Figure 4 is a flow diagram of an illustrative method for determining permeability based on collar responses;

Figure 5 is an illustrative graph of non-differential responses;

Figure 6 is an illustrative graph of differential responses in a single pipe scenario;

Figure 7 is an illustrative graph of differential responses in a double pipe scenario; and

Figure 8 is a contextual view of a logging while drilling (LWD) environment.

It should be understood, however, that the specific embodiments given in the drawings and detailed description thereto do not limit the disclosure. On the contrary, they provide the foundation for one of ordinary skill to discern the alternative forms, equivalents, and modifications that are encompassed together with one or more of the given embodiments in the scope of the appended claims.

Notation and Nomenclature

Certain terms are used throughout the following description and claims to refer to particular system components and configurations. As one of ordinary skill will appreciate, companies may refer to a component by different names. This document does not intend to distinguish between components that differ in name but not function. In the following discussion and in the claims, the terms "including" and "comprising" are used in an open-ended fashion, and thus should be interpreted to mean "including, but not limited to…". Also, the term "couple" or "couples" is intended to mean either an indirect or a direct electrical or physical connection. Thus, if a first device couples to a second device, that connection may be through a direct electrical connection, through an indirect electrical connection via other devices and connections, through a direct physical connection, or through an indirect physical connection via other devices and connections in various embodiments.

Detailed Description

The issues identified in the background are at least partly addressed by determining permeability based on collar responses. Accurate measurements of pipe thickness and pipe corrosion can be based on the permeability data, and corrosion monitoring can be especially useful to prevent pipe integrity failures in mature wells or non-producing wells. For example, corrosion damage typically decreases the thickness, and hence the conductivity, of casing strings. After transmitting an interrogation signal into the casing strings, the response received is a function of conductivity, and also serves as an indicator of the remaining wall thickness. The response is also a function of the permeability of the casing material, which is typically not constant and can exhibit large changes from one joint of casing to another. By measuring the permeability of the casing material at the collar, where the casing is much thicker, a more accurate measurement of casing conductivity and wall thickness of the casing walls between the collars may be determined.

The disclosed systems and methods for determining such permeabilities are best understood in terms of the context in which they are employed. As such, Figure 1 shows a well 102 including a casing string 104 positioned in a borehole 106 that has been formed in the earth by a drill bit. The casing string 104 includes multiple casing tubulars (usually 30-foot steel tubulars) connected end-to-end by collars 108. Cement 110 has been injected between an outer surface of the casing string 104 and an inner surface of the borehole 106, and the cement 110 has been allowed to set. The cement 110 enhances the structural integrity of the well 102 and seals the annulus around the casing 104 against undesired fluid flows. Though the well 102 is shown as entirely cemented, in practice certain intervals may be left without cement, e.g., in horizontal runs of the borehole where it may be desired to facilitate fluid flows.

Perforations 114 have been formed at one or more positions along the borehole 106 to facilitate the flow of a fluid 116 from a surrounding formation into the borehole 106 and thence to the surface. The casing string 104 may include pre-formed openings 118 in the vicinity of the perforations 114, or it may be perforated at the same time as the formation. Typically, the well 102 is equipped with a production tubing string positioned in an inner bore of the casing string 104. One or more openings in the production tubing string accept the borehole fluids and convey them to the earth's surface and onward to storage and/or processing facilities via a production outlet 120. The wellhead may include other ports such as a port 122 for accessing the annular space(s) and a blowout preventer 123 for blocking flows under emergency conditions. Various other ports and feed-throughs are generally included to enable the use of external sensors 124 and internal sensors. A cable 126 couples such sensors to a well interface system 128.

Figure 2 shows a contextual view of an illustrative wireline embodiment. A logging truck 202 suspends a tool 301, described in greater detail with respect to Figure 3, on a wireline cable 206 having conductors for transporting power to the tool 301 and telemetry from the tool 301 to the surface. The tool 301 may be conveyed through the borehole at variable depths, speeds, and azimuthal orientations, and the length of cable 206 deployed may be measured for depth estimation purposes. On the surface, a computer 208 acquires and stores measurement data from the tool 301 as a function of position along the borehole and as a function of azimuth. The computer 208 can take different forms including a tablet computer, laptop computer, desktop computer, and virtual cloud computer, and executes software to carry out necessary processing and enable the user to view and interact with a display of the resulting information. Specifically, a processor coupled to memory and located at the surface may execute the software. The software may collect the data and organize it in a file or database. The software may respond to user input via a keyboard or other input mechanism to display data as an image or movie on a monitor or other output mechanism such as a printer. In this way, a multi-dimensional representation of the surrounding formation, tubings, collars, and casing may be obtained, processed, and displayed. Furthermore, the software may issue an audio or visual alert to direct the user's attention to a particular location, result, or piece of data. The processor may perform any appropriate step described below. In at least one embodiment, the tool 301 itself may include the processor coupled with memory to obtain, store, and process measurement data taken by the sensors. In another embodiment, processors both at the surface and downhole may work together or independently to obtain, store, and process measurement data. Centralizers 210 keep the tool 301 centered within the borehole.

Figure 8 shows an illustrative drilling environment. A drilling platform 2 supports a derrick 4 having a traveling block 6 for raising and lowering a bottomhole assembly (BHA) 19. The platform 2 may also be located offshore for subsea drilling purposes in at least one embodiment. The BHA 19 may include one or more of a rotary steerable system, logging while drilling (LWD) system, drill bit 14, reamer, and downhole motor 26. A top drive 10 supports and rotates the BHA 19 as it is lowered through the wellhead 12. The drill bit 14 and reamer may also be driven by the downhole motor 26. As the drill bit 14 and reamer rotate, they create a borehole 17 that passes through various formations 18. A pump 20 circulates drilling fluid 24 through a feed pipe 22, through the interior of the drill string to the drill bit 14. The fluid exits through orifices in the drill bit 14 and flows upward to transport drill cuttings to the surface where the fluid is filtered and recirculated.

A data processing system 50 may be coupled to a measurement unit on the platform 2 by a wired connection 49 or wireless connection, and may periodically obtain data from the measurement unit as a function of position and/or time. Software (represented by information storage media 52) may run on the data processing system 50 to collect the data and organize it in a file or database. Specifically, a processor coupled to memory may execute the software. The software may respond to user input via a keyboard 54 or other input mechanism to display data as an image or movie on a monitor 56 or other output mechanism. The software may process the data to optimize oilfield operations as described below. In at least one embodiment, the data processing system 50 is located downhole within a housing able to protect the system 50 from the harsh downhole environment. In another embodiment, processors both at the surface and downhole may work together or independently to obtain, store, and process measurement data.

Figure 3 is a functional schematic view of an illustrative tool 301 for determining permeability based on collar responses. The tool 301 includes an eddy current sonde module

308, a sensor module 310, and a communication and processing module 312. The sonde module 308 includes a transmitter to transmit a primary electromagnetic field when in the casing string 306. As illustrated, the tool 301 is within three concentric casing strings (a “triple-pipe” scenario), but the tool 301 may be used with any number of casing strings 306. In some cases, the number of casing strings 306 may not be known because of the age of the well, the inaccessibility or incompleteness of records, and the like. The sonde module 308 also includes a receiver to receive collar responses including a secondary electromagnetic field produced, in response to the primary field, by the collars 304.

Figure 5 illustrates the manner in which the collar responses for each pipe contribute to the overall received signal. Specifically, the magnitude of the response is shown as a function of increasing distance from the surface in a vertical well (increasing depth), with peaks corresponding to the collar positions on the various casing strings. The largest responses correspond to the collars of the first, or innermost, casing string because there is less dissipation or spreading of the signal. Similarly, the smallest responses correspond to the collars of the third, or outermost, collars because there is more signal dissipation. However, even for the outermost casing, the response is still large enough to isolate and measure.

Returning to Figure 3, the sensor module 310 includes depth sensors, temperature sensors, pressure sensors, and the like that collect downhole measurements as a function of time. The data collected by these sensors may be associated with the signals transmitted and received by the sonde 308 module. For example, the received signal may be associated with downhole data corresponding to the time the signal was received. When associated, the collected measurements may provide context for interpreting and processing the signals.

The communication and processing module 312 includes a processor, memory, and communication hardware for processing operations, storing data, and enabling communications between the tool 301 and the surface. The communication channel between the tool 301 and the surface may be wired or wireless. The hardware on the tool 301 may be powered from the surface using a wireline 314 as a conduit, and the tool 301 itself may be centered within the borehole by centralizers 302. By conveying the tool 301 along the borehole, the permeability of the casings 306 may be determined by the processor and a representation of the casing 306 based on the permeability may be output for display by the processor as described with respect to Figure 4.

Figure 4 is a flow diagram of an illustrative method 400 of determining permeability based on collar responses beginning at 402 and ending at 416. At 404, the tool is conveyed through one or more concentric casings in a borehole. The number of casings or collars need not be known in advance. For vertical wells, the tool may be conveyed by wireline, and for horizontal wells, the tool may be conveyed by tractor. While being conveyed, the tool maybe rotated to different azimuthal orientations to take measurements at different depths and orientations.

At 406, a primary electromagnetic field is transmitted. The field, or signal, may be transmitted by a transmitter or transceiver coil on the tool. If the collars can be predictably located at certain depths, a depth sensor on the tool may alert the transmitter to fire at particular depths. If the collars cannot be predictably located, the tool may transmit based on other criteria measured by sensors on the tool. For example, particular temperature and/or pressure values may alert the transmitter to fire.

At 408, at least one collar response is received. The collar response includes a secondary electromagnetic field produced in response to the primary field by at least one collar. Typically, responses from different collars will present in the received signal, and these responses are isolated in order to measure and record their magnitude in context with other downhole data collected by sensors for a particular time, depth, and/or azimuth.

At 410, the permeability of the tubular string is determined based on the collar responses. In general, to determine the permeability, the collar response is compared with responses in a model or simulation. The model may be an electromagnetic simulation algorithm that is based on analytical formulas or numerical methods such as finite difference, finite-element, method of moments, or integral equations. The permeability of the simulation is adjusted until the simulated response is sufficiently similar to the collar response. The similarity may be measured as an L2-norm of the differences between the modeled measurement and real measurement. This value is typically called as the "cost function." A typical threshold may be selected as a level that corresponds to 0.1% of the real measurement magnitude. Minimization of the differences may be performed by using a numerical optimization algorithm such as Gauss-Newton, Levenberg-Marquardt, etc. Next, the permeability that minimizes the difference between the simulated response and collar response is selected as the permeability of the casing corresponding to the collar response. If there is a known relationship between the casing permeability and the collar permeability that is different than equivalence, then the selected permeability is adjusted according to this relationship as well. For example in cases where collar has a complicated or unknown 3D geometry, it may not be modeled with all details included and the numerical optimization result may be different than the actual permeability of the casing. In this case, a multiplicative correction factor can be calculated based on measurements in pipes with known permeability, and this factor can be applied for all subsequent pipes. In the optimization process, constraints may be used to limit the results to be in physical range. For example, casing permeability is not lower than 1 or higher than 150 in at least one embodiment. These conditions can be enforced during the iterations of numerical optimization.

Additionally, determining the permeability may include calculating differential responses, at various permeabilities, between the simulated collar response of the tubular string and a simulated non-collar response of the tubular string without the collar. Specifically, the complex voltage, phase, or magnitude of the peak of the simulated non-collar response is subtracted from the complex voltage, phase, or magnitude of the peak of the simulated collar response. Next, the absolute value of the difference is determined. This process is repeated over multiple permeability values, which are commonly denoted with the symbol μ. In this way, a library of collar responses may be built for comparison purposes.

Figure 6 illustrates a graph of the differential responses associated with the magnitude as a function of time. Specifically, the differential responses using μ values of 1, 20, 40, 60. 80, and 100 are shown for a single pipe with an outer diameter of 5 inches, a thickness of 0.362 inches, and a collar length of 5 inches. Over time the differential responses converge, but they are well differentiated before convergence. As such, the actual collar response can be compared to the simulated collar response during a time window in which the differential responses are sufficiently separated. For example, they may be required to be separated by a response value equal to a multiple of expected measurement error. According to Figure 6, the comparison may occur before 60 milliseconds. However, Figure 7 illustrates the differential responses in a double-pipe scenario for μ values of 20, 40, 60, 80, and 100 for pipes with outer diameters of 5 inches and 9 5/8 inches, thicknesses of 0.362 inches, and collar lengths of 5 inches. Here, the comparison may occur between 40 and 80 milliseconds. Returning to Figure 4, the actual collar responses at these times may be extracted from the received signal at 408.

For a case where the pipe on one side of the collar is a different material or permeability than the pipe on the other side of the collar, calculating the differential responses may include calculating two differential responses. The first set of differential response may be for the upper pipe above the collar, and the second set of differential responses may be for the lower pipe below the collar. In a similar fashion, portions of the same pipe may include different materials or permeability leading to determination of a separate set of differential responses.

In at least one embodiment, the permeability of an innermost casing is determined first. High frequencies or a very shallow pad type measurement device may be used. For example, frequencies between 20 Hz and 1 MHz may be used. Next, this permeability is used during the determination of the permeability of the next innermost casing. In this way, permeabilities of the casings are determined from innermost to outermost. For a case where multiple collar responses are recorded, determining the permeability may include determining the permeability of the pipe based on an average magnitude of collar responses.

At 412, a representation of the casing is displayed based on the permeability. Specifically, the thickness and corrosion characteristics of the casing (both of which are a function of the permeability) may be displayed to a user. Different colors, lines, and symbols may identify different characteristics on the display. For example, each casing thickness may be plotted as separate curves. Alternatively, changes in the casing thicknesses may be displayed as changes in the color. A red hue may be used for metal losses, and a green hue may be used for metal gains. By repeating and displaying the measurements over time, the corrosion of the casing may be monitored.

Determining casing, or any tubing, permeability based on collar responses has several advantages. First, the collar responses are stronger than non-collar responses. As such, the determination is more accurate. Second, by not ignoring the collar, a more complete set of data is used in the determination. Again, this makes the determination more accurate. Accordingly, the thickness and corrosion estimates of the casing are more accurate as well.

In at least one embodiment, a method for determining tubing permeability includes conveying a tool through a tubular string in a borehole. The tool includes a transmitter that transmits a primary electromagnetic field and a receiver that receives at least one collar response. The collar response includes a secondary electromagnetic field produced in response to the primary field by a collar in the tubular string. The method further includes determining a permeability of at least one portion of the tubular string based on a magnitude of the at least one collar response. The method further includes displaying a representation of the at least one portion of the tubular string based on the permeability.

In another embodiment, an apparatus for determining tubing permeability includes a transmitter to transmit a primary electromagnetic field when in a tubular string. The apparatus further includes a receiver to receive at least one collar response including a secondary electromagnetic field produced in response to the primary field by a collar in the tubular string. The apparatus further includes a processor to determine a permeability of at least one portion of the tubular string based on a magnitude of the at least one collar response.

In another embodiment, a system for determining tubing permeability includes depth sensors to determine a depth when in a tubular string. The system further includes an eddy current sonde including a transmitter to transmit a primary electromagnetic field when in the tubular string and a receiver to receive at least one collar response including a secondary electromagnetic field produced in response to the primary field by a collar in the tubular string. The system further includes a communication module including a processor to determine a permeability of at least one portion of the tubular string based on a magnitude of the at least one collar response and memory to store collar response data.

The following features may be incorporated into the various embodiments. Corrosion of the at least one portion of the tubular string may be monitored by determining a thickness of the at least one portion based on the permeability. Differential responses, at various permeabilities, between a simulated collar response of the tubular string and a simulated non-collar response of the tubular string without the collar may be calculated. The collar response may be compared to the simulated collar response during a time window in which the differential responses do not converge. A permeability corresponding to the simulated collar response most similar to the collar response during the time window may be selected as the permeability of the at least one portion of the tubular string. Two differential responses may be calculated, one for an upper tubular portion above the collar and one for a lower tubular portion below the collar, the upper and lower portions including different permeabilities. The at least one collar response may be extracted from a signal received by the receiver. The receiver may receive collar responses from collars located at different radial distances from the tool. The permeability of at the least one portion of the tubular string may be determined based on an average magnitude of more than one collar response. A processor may output for display a representation of the at least one portion of the tubular string based on the permeability. The representation may show thickness as a function of permeability along the length of the borehole. The representation may show thickness as a function of permeability around the azimuth of the borehole.

A processor may calculate differential responses, at various permeabilities, between a simulated collar response of the tubular string and a simulated non-collar response of the tubular string without the collar. A processor may compare the collar response to the simulated collar response during a time window in which the differential responses do not converge. A processor may extract the at least one collar response from a signal received by the receiver. A receiver may receive collar responses from collars located at different radial distances from the tool. A processor may determine the permeability of at the least one portion of the tubular string based on an average magnitude of more than one collar response.

While the present disclosure has been described with respect to a limited number of embodiments, those skilled in the art will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover all such modifications and variations.

CLAIMS

WHAT IS CLAIMED IS:

1. A method for determining tubing permeability comprising:

conveying a tool through a tubular string in a borehole, the tool comprising a transmitter that transmits a primary electromagnetic field, the tool further comprising a receiver that receives at least one collar response comprising a secondary electromagnetic field produced in response to the primary field by a collar in the tubular string;

determining a permeability of at least one portion of the tubular string based on a magnitude of the at least one collar response; and

displaying a representation of the at least one portion of the tubular string based on the permeability.

2. The method of claim 1, further comprising monitoring corrosion of the at least one portion of the tubular string by determining a thickness of the at least one portion based on the permeability.

3. The method of claim 1, wherein determining the permeability further comprises calculating differential responses, at various permeabilities, between a simulated collar response of the tubular string and a simulated non-collar response of the tubular string without the collar.

4. The method of claim 3, wherein determining the permeability further comprises comparing the collar response to the simulated collar response during a time window in which the differential responses are substantially different.

5. The method of claim 4, wherein determining the permeability further comprises selecting a permeability corresponding to the simulated collar response most similar to the collar response during the time window as the permeability of the at least one portion of the tubular string.

6. The method of claim 3, wherein calculating differential responses comprises calculating two differential responses, one for an upper tubular portion above the collar and one for a lower tubular portion below the collar, the upper and lower portions comprising different permeabilities.

7. The method of claim 1, wherein determining the permeability further comprises extracting the at least one collar response from a signal received by the receiver.

8. The method of claim 1, wherein the receiver receives collar responses from collars located at different radial distances from the tool.

9. The method of claim 1, wherein determining the permeability comprises determining the permeability of at the least one portion of the tubular string based on an average magnitude of more than one collar response.

10. An apparatus for determining tubing permeability comprising:

a transmitter to transmit a primary electromagnetic field when in a tubular string;

a receiver to receive at least one collar response comprising a secondary electromagnetic field produced in response to the primary field by a collar in the tubular string; and

a processor to determine a permeability of at least one portion of the tubular string based on a magnitude of the at least one collar response.

11. The apparatus of claim 10, wherein the processor outputs for display a representation of the at least one portion of the tubular string based on the permeability.

12. The apparatus of claim 11, wherein the representation shows thickness as a function of permeability along the length of the borehole.

13. The apparatus of claim 12, wherein the representation shows thickness as a function of permeability around the azimuth of the borehole.

14. The apparatus of claim 10, wherein the processor calculates differential responses, at various permeabilities, between a simulated collar response of the tubular string and a simulated non-collar response of the tubular string without the collar.

15. The apparatus of claim 14, wherein the processor compares the collar response to the simulated collar response during a time window in which the differential responses do not converge.

16. The apparatus of claim 10, wherein the processor extracts the at least one collar response from a signal received by the receiver.

17. The apparatus of claim 10, wherein the receiver receives collar responses from collars located at different radial distances from the tool.

18. The apparatus of claim 10, wherein the processor determines the permeability of at the least one portion of the tubular string based on an average magnitude of more than one collar response.

19. A system for determining tubing permeability comprising:

depth sensors to determine a depth when in a tubular string;

an eddy current sonde comprising a transmitter to transmit a primary electromagnetic field when in the tubular string and a receiver to receive at least one collar response comprising a secondary electromagnetic field produced in response to the primary field by a collar in the tubular string; and

a communication module comprising a processor to determine a permeability of at least one portion of the tubular string based on a magnitude of the at least one collar response and memory to store collar response data.

20. The system of claim 19, wherein determining the permeability further comprises calculating differential responses, at various permeabilities, between a simulated collar response of the tubular string and a simulated non-collar response of the tubular string without the collar.

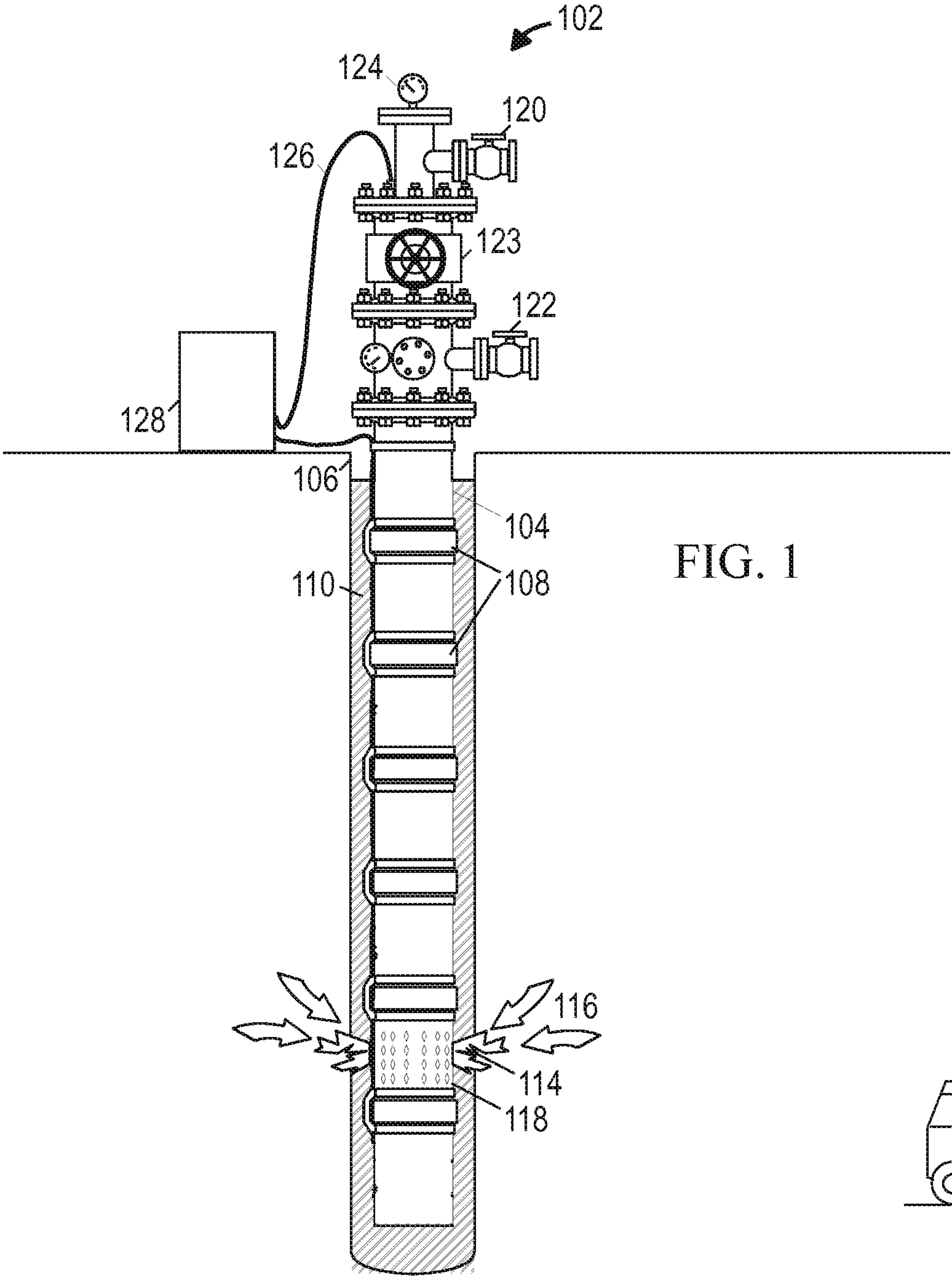

102
124
120
126
123
122
128
106
104
110
108
116
114
118

FIG. 1

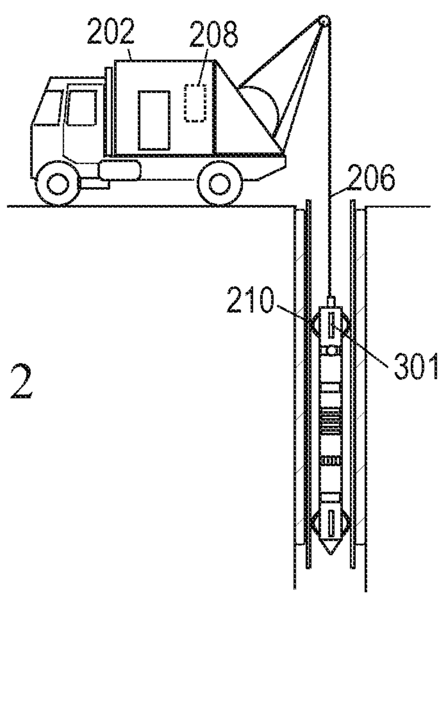

202
208
206
210
301

FIG. 2

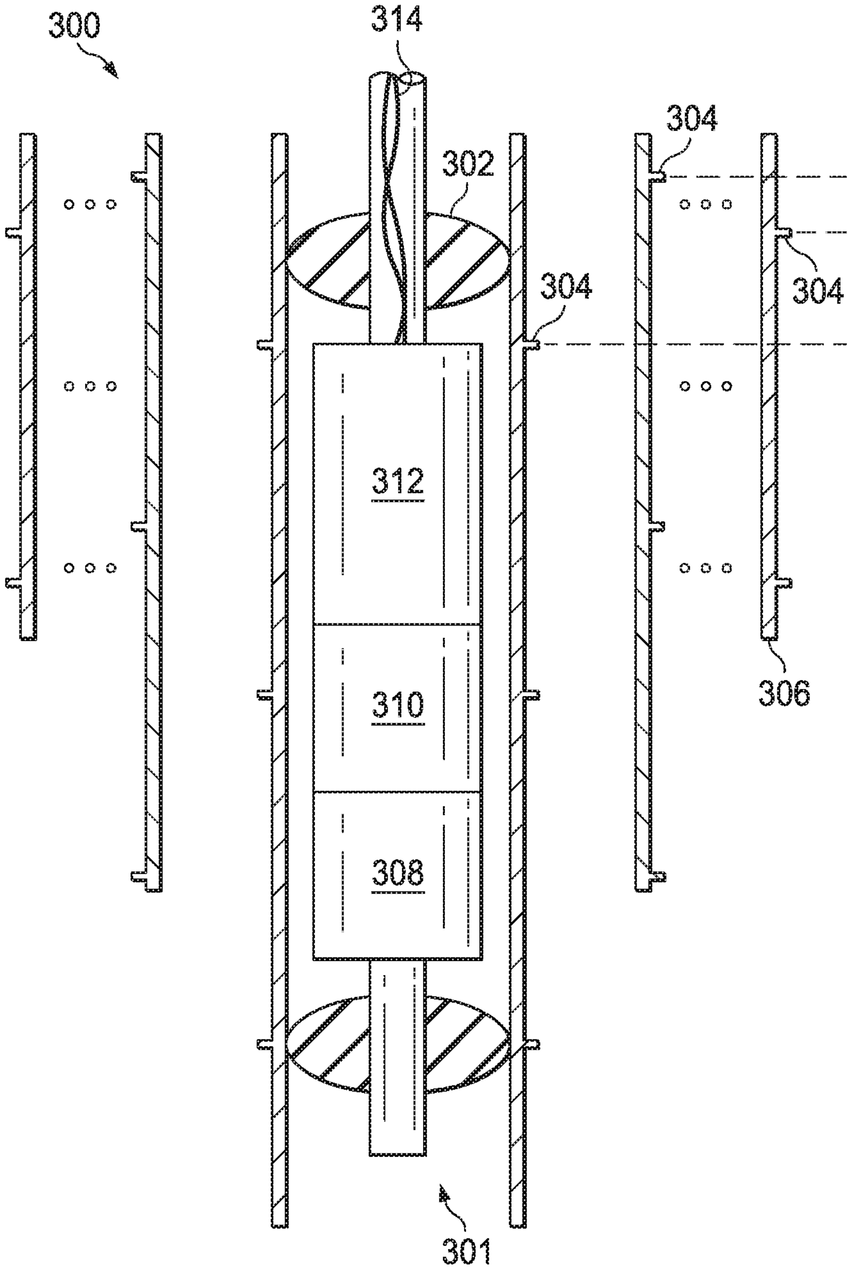


FIG. 3

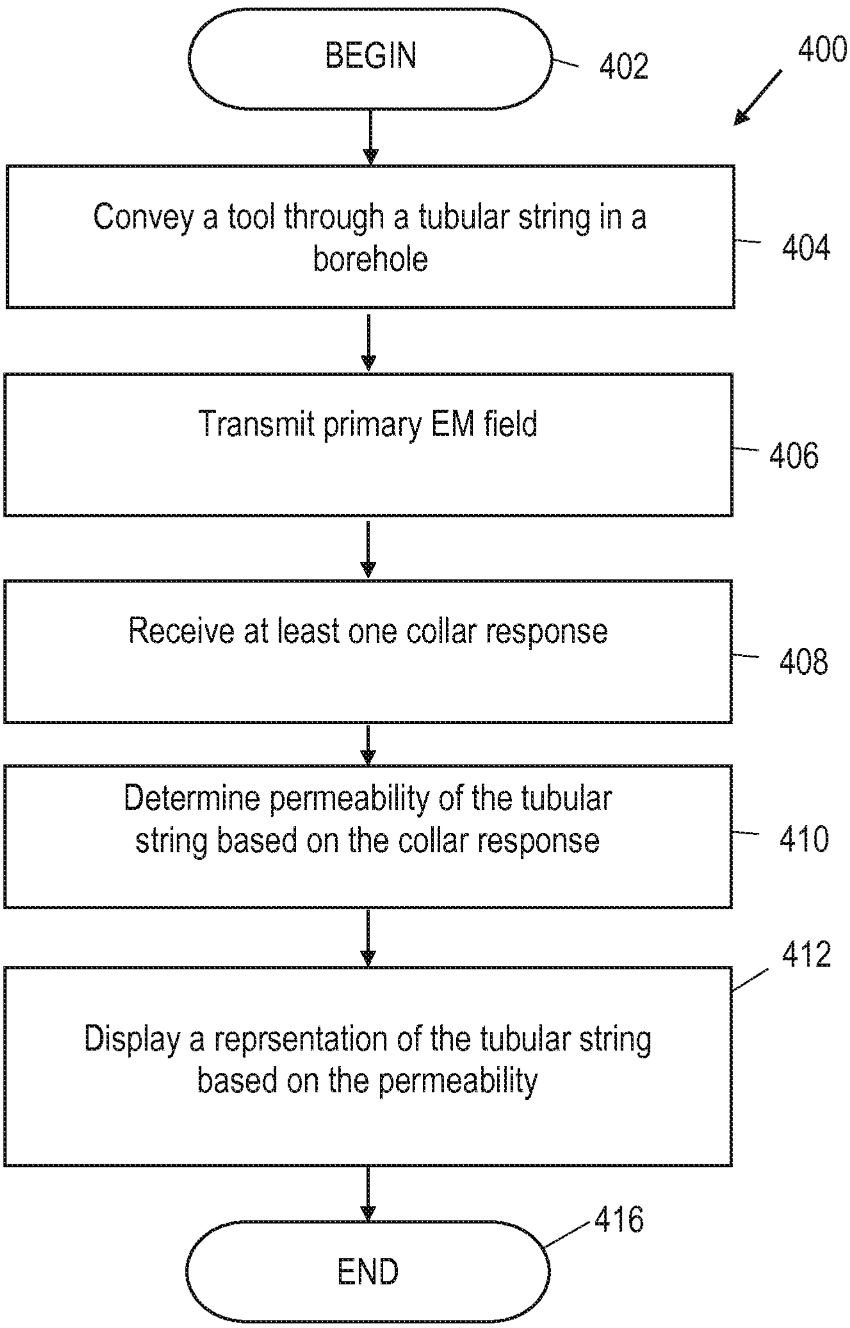

BEGIN
402
400
Convey a tool through a tubular string in a borehole
404
Transmit primary EM field
406
Receive at least one collar response
408
Determine permeability of the tubular string based on the collar response
410
412
Display a reprsentation of the tubular string based on the permeability
END
416

FIG. 4

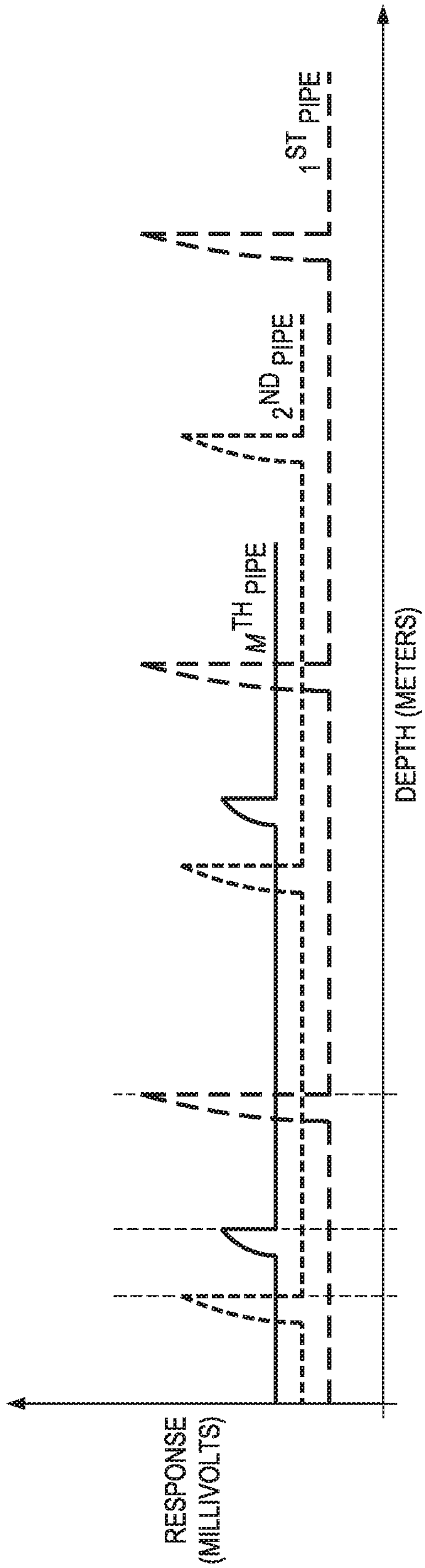

1ST PIPE
2ND PIPE
MTH PIPE
DEPTH (METERS)
RESPONSE
(MILLIVOLTS)

FIG. 5

FIG. 6

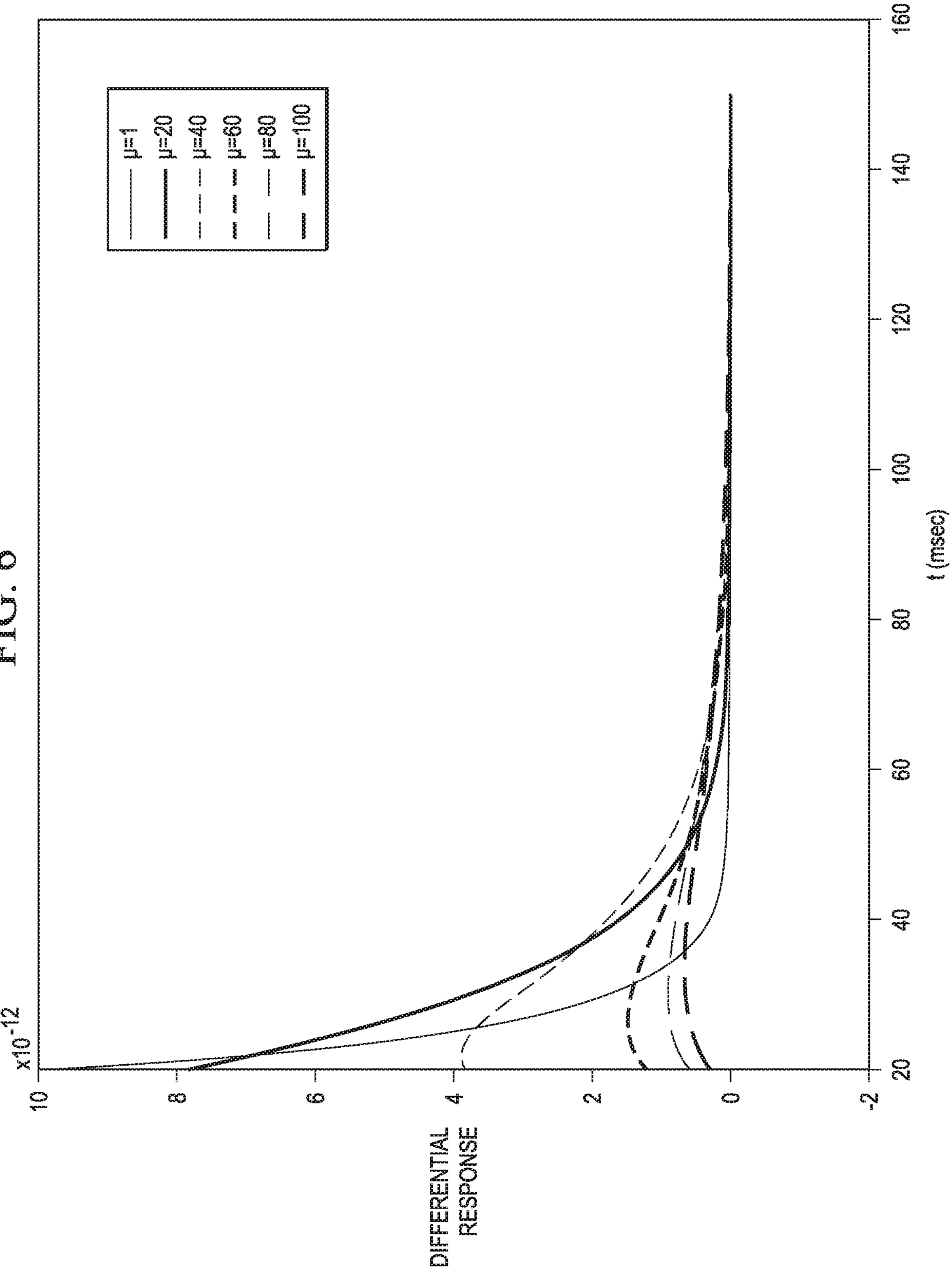
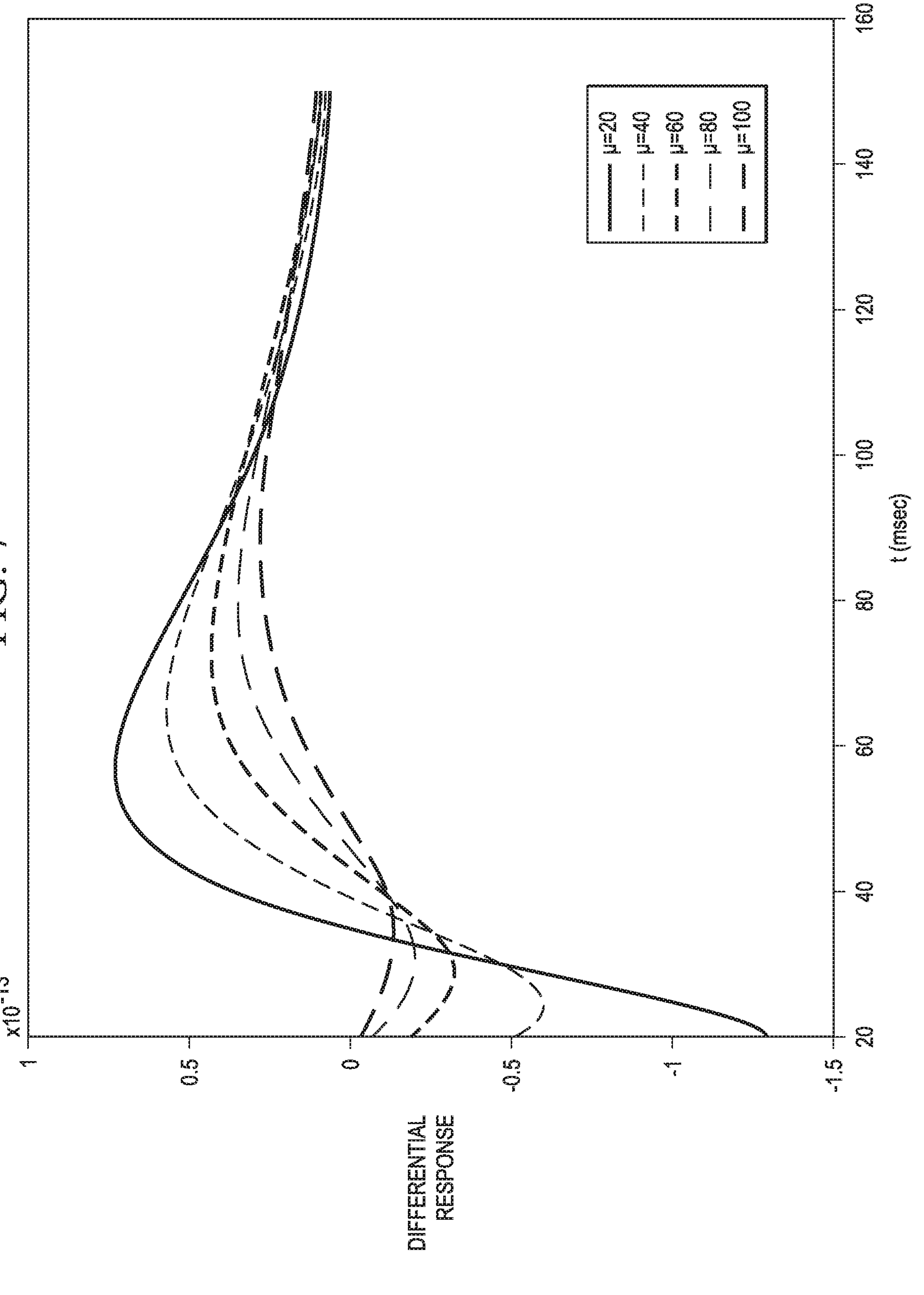

x10^-12
10
8
6
4
2
0
-2
DIFFERENTIAL RESPONSE
20
40
60
80
100
120
140
160
t (msec)
μ=1
μ=20
μ=40
μ=60
μ=80
μ=100

FIG. 7


DIFFERENTIAL RESPONSE
x10^{-13}
1
0.5
0
-0.5
-1
-1.5
20
40
60
80
100
120
140
160
t (msec)
μ=20
μ=40
μ=60
μ=80
μ=100

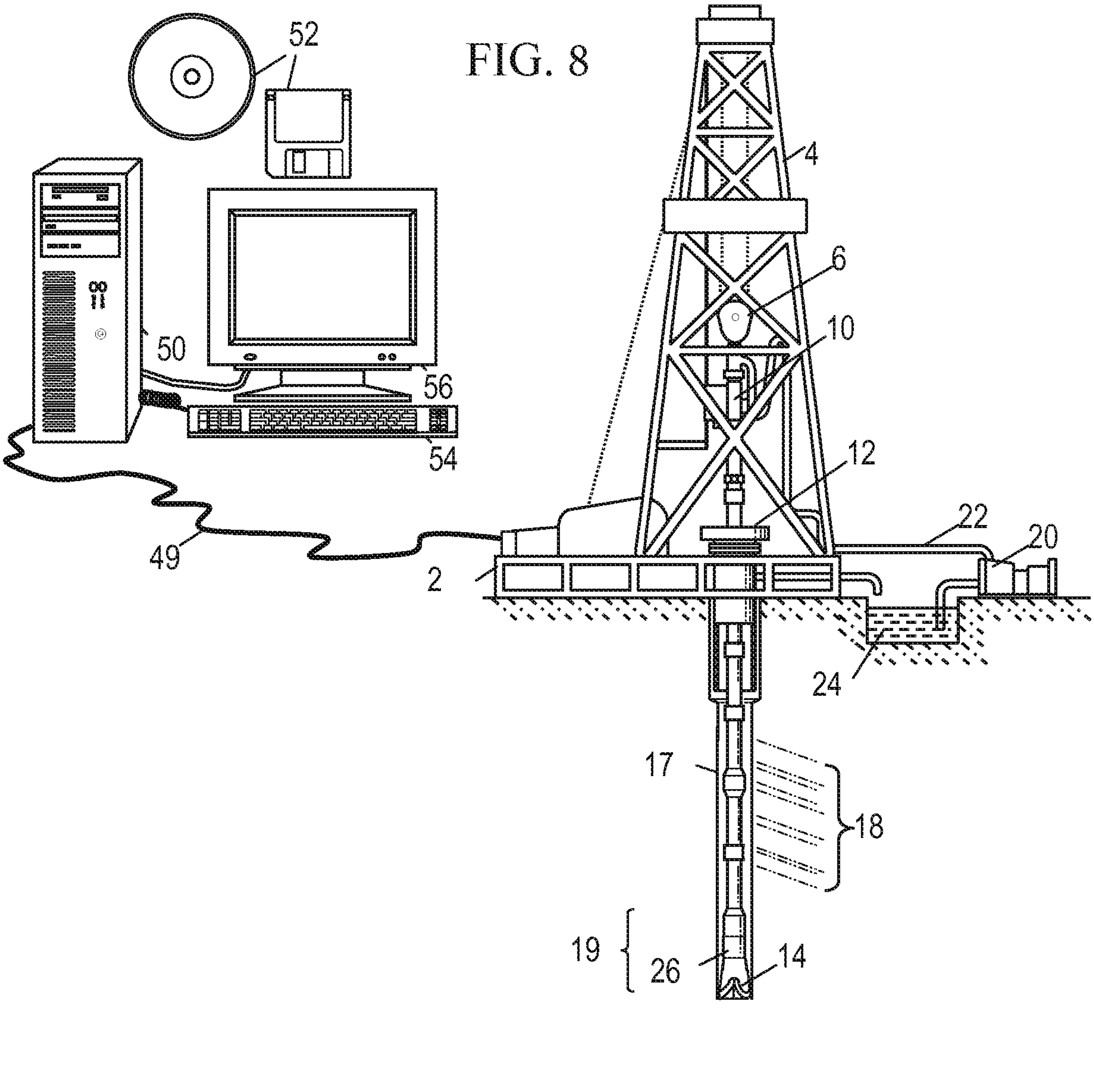


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/050763

A. CLASSIFICATION OF SUBJECT MATTER

E21B 47/00(2006.01)i, G01V 3/18(2006.01)i, G01V 3/38(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B 47/00; G01D 1/40; G01D 5/12; E21B 49/00; G01N 27/72; E21B 31/06; E21B 47/12; G01V 3/18; G01V 3/38

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & keywords: permeability, transmitter, receiver, electromagnetic field, collar, thickness

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4736298 A (EASTON et al.) 05 April 1988 See column 3, lines 28-50 and claim 11.	1-2,7-13,16-19
A		3-6,14-15,20
A	US 2014-0216734 A1 (SCHLUMBERGER TECHNOLOGY CORPORATION) 07 August 2014 See abstract and paragraphs [0019]-[0022].	1-20
A	US 2006-0202700 A1 (BAROLAK et al.) 14 September 2006 See abstract and claim 1.	1-20
A	US 2011-0308789 A1 (ZHANG et al.) 22 December 2011 See paragraph [0021] and claim 1.	1-20
A	US 2011-0290011 A1 (DOWLA et al.) 01 December 2011 See abstract, claim 1, and figure 2.	1-20

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent 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 when the document is taken alone
"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

Date of the actual completion of the international search	Date of mailing of the international search report
30 May 2016 (30.05.2016)	**30 May 2016 (30.05.2016)**

Name and mailing address of the ISA/KR
International Application Division
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon, 35208, Republic of Korea
Facsimile No. +82-42-481-8578

Authorized officer
LEE, Dal Kyong
Telephone No. +82-42-481-8440

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US2015/050763

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 4736298 A	05/04/1988	None	
US 2014-0216734 A1	07/08/2014	WO 2014-123800 A1	14/08/2014
		WO 2014-123800 A9	02/10/2014
US 2006-0202700 A1	14/09/2006	CA 2600439 A1	21/09/2006
		CA 2600439 C	20/05/2014
		CA 2692550 A1	21/09/2006
		CA 2692550 C	19/11/2013
		CA 2692554 A1	21/09/2006
		CA 2692554 C	15/10/2013
		EP 1856517 A1	21/11/2007
		EP 1856517 A4	09/03/2011
		EP 1856517 B1	18/09/2013
		US 2006-0202685 A1	14/09/2006
		US 2006-0202686 A1	14/09/2006
		US 7403000 B2	22/07/2008
		US 7595636 B2	29/09/2009
		US 7795864 B2	14/09/2010
		WO 2006-099133 A1	21/09/2006
US 2011-0308789 A1	22/12/2011	CA 2745112 A1	10/06/2010
		EP 2368141 A1	28/09/2011
		EP 2368141 B1	13/02/2013
		US 9069097 B2	30/06/2015
		WO 2010-065208 A1	10/06/2010
US 2011-0290011 A1	01/12/2011	US 9175559 B2	03/11/2015
		WO 2010-040045 A2	08/04/2010
		WO 2010-040045 A3	22/07/2010