

FIBER OPTICS TO MONITOR PIPELINE CATHODIC PROTECTION SYSTEMS

CLAIM OF PRIORITY

[0001] This application claims priority to U.S. Patent Application No.
5 14/989,582, filed on January 6, 2016, the entire contents of which are hereby
incorporated by reference.

TECHNICAL FIELD

[0002] This disclosure relates to pipelines, for example, pipelines that carry
hydrocarbons, monitored using fiber optic technology.

BACKGROUND

10 [0003] Pipelines made of steel are used to transport hydrocarbons, for example,
as underground hydrocarbon pipelines. Such pipelines are also used in hydrocarbon
operations, for example, wellbore drilling and hydrocarbon recovery from a
hydrocarbon reservoir to the surface. Corrosion, both internal and external, is
15 responsible for a large quantity of failures in such pipelines. Corrosion is caused by
the degradation of metal by a chemical reaction between the metal and non-metallic
matter such as water, oxygen, sulfur, or other non-metallic matter. Corrosion causes
the metal to return to the form in which the metal originally existed as an ore with
complete loss of metallic properties.

20 [0004] Sometimes, cathodic protection (CP) systems are used to mitigate
corrosion in pipelines, for example, in specific locations of underground pipelines,
such as road crossings, camel crossings, or other locations. CP systems are also used
at certain locations in horizontal direct drilling strings. In a CP system, the metal
surface is made the cathode of an electrochemical cell. A sacrificial CP system is an
25 example of a CP system in which the surface of the metal (e.g., the hydrocarbon
pipeline) is connected to a mass of less noble metal buried or immersed into common
electrolyte. The less noble metal is a sacrificial metal that acts as an anode and
corrodes instead of the protected metal. An impressed current CP system is another
example of a CP system in which the metal surface is connected to the negative of a

direct current (DC) power supply. The positive of the DC power supply is connected to a number of anodes buried in the ground or impressed in soil or water.

SUMMARY

[0005] This disclosure describes fiber optics to monitor pipeline CP systems.
5 This disclosure also describes monitoring of current in CP systems in certain underground pipeline locations such as road crossings. This disclosure additionally describes monitoring of current in CP systems in horizontal directional drilling of pipelines. As described below, fiber optic technology is used to monitor the current of the CP systems.

10 [0006] In some aspects, a system includes a cathodic protection system coupled to a hydrocarbon pipeline. The cathodic protection system is configured to pass a current through the hydrocarbon pipeline to control corrosion of the hydrocarbon pipeline. A fiber optic system is connected to the cathodic protection system. The fiber optic system is configured to measure the current flowing through
15 the hydrocarbon pipeline over time, and provide the measured current.

[0007] This, and other aspects, can include one or more of the following features. The fiber optic system can include a fiber optic cable connected to the hydrocarbon pipeline. A light generator can be connected to the fiber optic cable. The light generator can be configured to generate light to pass through the fiber optic cable.
20 A polarimeter can be connected to the fiber optic cable. The polarimeter can be configured to detect reflected light that passes through the fiber optic cable. The reflect light can be generated in response to a reflection of the generated light. A signal processor can be connected to the fiber optic cable, the light generator and the polarimeter. The signal processor can be configured to determine a quantity of current
25 flowing through the hydrocarbon pipeline at a time instant based at least on a magnetic field generated by the current flowing through the hydrocarbon pipeline and the reflection of the light passing through the fiber optic cable. The signal processor can be configured to detect multiple quantities of current at a corresponding multiple time instants. The signal processor can be configured to determine a current density of the
30 current flowed through the hydrocarbon pipeline by the cathodic protection system and compare the determined current density with a threshold current density. Based on a

result of the comparing, the signal processor can be configured to determine that the current density satisfies the threshold density. Based on a result of the comparing, the signal processor can be configured to determine that the current density does not satisfy the threshold current density and cause the cathodic protection system to
5 modify a specified current passed to the hydrocarbon pipeline to modify the current density to satisfy the threshold current density. The fiber optic cable can be coiled around a length of the hydrocarbon pipeline. The hydrocarbon pipeline can be an underground hydrocarbon pipeline and can include a first portion and a third portion positioned in aerated soil, and a second portion positioned in non-aerated soil and
10 between the first portion and the third portion. The fiber optic cable can be coiled around each of the first portion, the second portion and the third portion. The hydrocarbon pipeline can be a horizontal drill string in a horizontal wellbore drilling system. The cathodic protection system can be configured to pass a specified current to the hydrocarbon pipeline and the fiber optic system can be configured to detect the
15 current flowing through the hydrocarbon pipeline over time while hydrocarbons are flowing through the hydrocarbon pipeline.

[0008] In some aspects, a method includes passing a specified quantity of current to an underground hydrocarbon pipeline to control external corrosion of the underground hydrocarbon pipeline. A quantity of current flowing through the
20 underground hydrocarbon pipeline is affected by the external corrosion of the underground hydrocarbon pipeline. The method includes monitoring reflected light passing through a fiber optic cable connected to the underground hydrocarbon pipeline. The reflected light is modulated by a magnetic field produced by the quantity of current flowing through the underground hydrocarbon pipeline. The method
25 includes determining, based on the monitored reflected light, the quantity of current flowing through the underground hydrocarbon pipeline.

[0009] This, and other aspects, can include one or more of the following features. Determining the quantity of the current flowing through the underground hydrocarbon pipeline can include determining multiple quantities of current flowing
30 through the underground hydrocarbon pipeline at corresponding multiple time instants. A current density of the current flowed through the underground hydrocarbon pipeline by the cathodic protection system can be determined and compared with a threshold

current density. Based on a result of the comparing, it can be determined that the current density satisfies the threshold density. Or, based on a result of the comparing, it can be determined that the current density does not satisfy the threshold current density. The specified current passed to the underground hydrocarbon pipeline can be
5 modified to satisfy the threshold current density. To connect the fiber optic cable to the underground hydrocarbon pipeline, the fiber optic cable can be coiled around a length of the underground hydrocarbon pipeline. The underground hydrocarbon pipeline can include a first portion and a third portion positioned in aerated soil, and a second portion positioned in non-aerated soil and between the first portion and the
10 third portion. The fiber optic cable can be coiled around each of the first portion, the second portion and the third portion. The hydrocarbon pipeline can be a horizontal drill string in a horizontal wellbore drilling system.

[0010] In some aspects, a method includes coiling a fiber optic cable around an underground hydrocarbon pipeline connected to a cathodic protection system
15 configured to pass a specified quantity of current to the underground hydrocarbon pipeline to control external corrosion of the underground hydrocarbon pipeline. A quantity of current flowing through the underground hydrocarbon pipeline is affected by the external corrosion of the underground hydrocarbon pipeline. Light is passed through the fiber optic cable. Reflected light passing through a fiber optic cable in
20 response to the light is monitored. The reflected light is modulated by the quantity of current flowing through the underground hydrocarbon pipeline. Based on the monitored reflected light, the quantity of current flowing through the underground hydrocarbon pipeline is monitored.

[0011] The details of one or more implementations of the subject matter
25 described in this specification are set forth in the accompanying drawings and the description below. Other features, aspects, and advantages of the subject matter will become apparent from the description, the drawings, and the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] FIG. 1 is an example of a schematic diagram of a fiber optic cathodic
30 protection monitoring system.

[0013] FIG. 2 is an example of a schematic diagram of a fiber optic cathodic protection monitoring system.

[0014] FIGS. 3A and 3B are examples of schematics of cathodic protection systems.

5 [0015] FIG. 4 is a flowchart of an example process of determining current flowing through a hydrocarbon pipeline.

[0016] FIG. 5 is a flowchart of an example process of monitoring current from a CP system flowing through a hydrocarbon pipeline.

10 [0017] Like reference numbers and designations in the various drawings indicate like elements.

DETAILED DESCRIPTION

[0018] Cathodic protection (CP) systems are used to mitigate corrosion, for example, external corrosion, in underground pipelines, for example, in specific locations of the pipelines, such as road crossings, camel crossings or other specific
15 locations. CP systems are also used at certain locations in horizontal direct drilling strings. In such CP systems, a current (for example, direct current) is applied to the specific location of the pipeline. This disclosure describes a fiber optics-based real-time measurement system of the CP current. To measure the current, a length of fiber optic cable is coiled around a section of the pipeline. The CP system passes current to
20 the section of the pipeline. The current that actually flows through the pipeline can be different from the current that the CP system passes to the pipeline, in part, due to pipeline corrosion. The light transmitted through the fiber optic cable is modulated by the current. The modulation is measured and converted into the current that flows through the section of the pipeline. In this manner, the current applied to the section of
25 the pipeline can be measured in real-time.

[0019] FIG. 1 is an example of a schematic diagram of a fiber optic cathodic protection monitoring system. The system includes a CP system 102 coupled to a hydrocarbon pipeline 104. The hydrocarbon pipeline 104 can be any sub-surface pipeline that is susceptible to corrosion. For example, the hydrocarbon pipeline 104
30 can be made from steel or other material that can corrode when buried beneath the surface. In some implementations, the hydrocarbon pipeline 104 can be used to

transport hydrocarbons (for example, petroleum, natural gas, combinations of them or other hydrocarbons) between two locations. Alternatively or in addition, any pipeline through which fluids can be flowed (for example, drilling fluids, hydraulic fracturing fluids, or other fluids) can be implemented.

5 [0020] The CP system 102 can be configured to pass a current through the hydrocarbon pipeline 104 to control corrosion of the pipeline 104. External corrosion of the pipeline 104 is caused by reactions between the pipeline 104 and the surrounding environment. The corrosion occurs when electrons move from the pipeline and combine with hydrogen atoms in the electrolyte. The electrolyte, for
10 example, can include the sand surrounding the pipelines which can have a concentration of hydrogen atoms. A quantity of corrosion can depend on the environment in which the hydrocarbon pipeline 104 is buried. For example, the hydrocarbon pipeline 104 can be buried in a desert environment with road crossings or camel crossings (or both). In some portions of such an environment, the possibility of
15 pipeline corrosion is high due to increased oxygen concentration.

 [0021] The CP system 102 can be implemented to mitigate corrosion in the hydrocarbon pipeline 104 by applying an electrical current that will pass through the soil to the pipelines (represented in FIG. 1 by electric current lines 104a and 104b that show a direction of the current). As described below, the CP system 102 can pass a
20 specified quantity of current to the hydrocarbon pipeline 104 to mitigate a corrosion in the pipeline 104. As the resistance of the current path changes, a quantity of current that actually flows through the hydrocarbon pipeline 104 also changes. The resistance of the current path is affected by factors including, for example, a thickness of coatings on the hydrocarbon pipeline 104, soil resistivity, or other factors that contribute to
25 external corrosion of the pipeline 104. Knowing a quantity of current flowing through the hydrocarbon pipeline 104 not only provides information about a quantity of corrosion in the pipeline 104 but also provides information about the coatings (for example, a thickness of the coatings) and soil resistivity. Knowing the quantity of current also provides information about the condition of the CP system 102, for
30 example, if the system is passing a required quantity of current to the pipeline 104. The information gathered by monitoring the quantity of current flowing through the

pipeline 104 can be used to optimize the CP system 104 based on the pipeline coatings, pipeline contents, soil resistivity or combinations of them.

[0022] The system includes a fiber optic system 106 connected to the CP system 102. As described below, the fiber optic system 106 is configured to measure the current flowing through the hydrocarbon pipeline 104 over time and to provide the detected current. For example, the quantity of current flowing through the pipeline 104 can generate a magnetic field around the pipeline 104. A strength of the magnetic field can vary with current, which, in turn, can vary based on factors such as those described above. A light signal carried by a fiber optic cable can be modulated by the magnetic field. As described below, the fiber optic system 106 can determine the quantity of current flowing through the hydrocarbon pipeline 104 based on the modulation of the light signal. In some implementations, the system 106 can include transmitters (not shown) that can transmit the detected current to a remote central system over networks (for example, wide area networks, satellite networks, other networks or combinations of them). As described in detail below, operators of the remote central system can determine if a quantity of current flowing through the hydrocarbon pipeline 104 is sufficient to mitigate external corrosion in light of the soil conditions and pipeline conditions (for example, coating thickness).

[0023] In some implementations, the system can include multiple test stations (for example, a first test station 108a, a second test station 108b, and more or fewer test stations). The test stations can be located above the surface, for example, in immediate proximity to the CP system 102 or the fiber optic system 106. Alternatively or in addition, the test stations can be located above the surface, for example, at remote locations. Each test station can be operated to measure the pipe to soil potential.

[0024] The fiber optic system 106 can include a fiber optic cable 110 connected to the hydrocarbon pipeline 104. In some implementations, the fiber optic cable 110 can be coiled around a length L of the hydrocarbon pipeline 104. In some implementations, the length of the underground pipeline 104 can include a first portion 118a, a second portion 118b and a third portion 118c. The first portion 118a and the third portion 118c can be positioned in one type of soil, for example, aerated soil 120a and 120c, respectively. The second portion 118b can be positioned in a different type of soil, for example, non-aerated soil 120b. For example, the second portion 118b can

be a road crossing or a camel crossing sandwiched between two desert environments. The fiber optic cable 110 can be coiled around each of the first portion 118a, the second portion 118b and the third portion 118c. In some implementations, a number of coils of the fiber optic cable in each section can be varied to obtain different current
5 density values in different portions of the pipeline. The current density value is representative of the resistivity of the soil in which a portion of the pipeline is buried.

[0025] The fiber optic system 106 can also include a light generator 112 connected to the fiber optic cable. In some implementations, the light generator 112 is a laser source. For example, the light generator 112 can be an opto-electronics module
10 light source of a fiber-pigtailed laser with a wavelength of substantially 1500 nm. The light generator 112 can be coupled to an end of the fiber optic cable 110. The fiber optic cable 110 can carry light generated by the light generator 112 through the fiber optic cable 110 connected to (for example, coiled around) the length of the hydrocarbon pipeline 104. The fiber optic cable 110 can also carry reflected light
15 generated in response to the light carried through the cable 110. A fiber Bragg grating (FBG) can be used to reflect the light. For example, the FBG can be a type of distributed Bragg reflector which reflects specific wavelengths of light while transmitting other wavelengths.

[0026] The fiber optic system 106 can include a polarimeter 114 connected to
20 the fiber optic cable 110. The polarimeter can detect the reflected light that passes through the fiber optic cable 110. The fiber optic system 106 additionally includes a signal processor 116 connected to the fiber optic cable 110, the light generator 112 and the polarimeter 114. The signal processor 116 can be implemented as a computer-readable medium storing instructions executable by one or more computer processors
25 to perform operations described here. Alternatively or in addition, the signal processor 116 can be implemented as processing circuitry configured to perform operations described here.

[0027] As described above, the quantity of current flowing through the hydrocarbon pipeline 104 generates a magnetic field around the pipeline 104. The
30 signal processor 116 can determine a quantity of current flowing through the hydrocarbon pipeline 104 at a time instant based on a strength of the magnetic field and properties of the reflected light carried through the fiber optic cable 110. In some

implementations, the light generator 112, the polarimeter 114 and the signal processor 116 can be housed in a single housing. Alternatively, each component or any combination of the three components can be positioned in a respective housing. In some implementations, the fiber optic system 106 can be positioned above the surface, for example, at or near a test station.

[0028] FIG. 2 is an example of a schematic diagram of a fiber optic cathodic protection monitoring system. The fiber optic cathodic protection monitoring system described with reference to FIG. 1 was implemented in a hydrocarbon pipeline 104 that transported hydrocarbons between locations. The system described with reference to FIG. 2 can be implemented in a hydrocarbon pipeline that is part of wellbore tubing 202. For example, the wellbore tubing 202 can be a drill string in horizontal wellbore drilling system 200. Alternatively, the wellbore tubing 202 can be a production string installed in a horizontal wellbore. In general, the hydrocarbon pipeline described here can be part of tubing used in any hydrocarbon-related operations in which tubing are installed vertically, horizontally or at angles such that portions of the tubing pass through different types of underground environments. In addition, the fiber optic system described here can be implemented to monitor, over time, current provided by the CP system to the hydrocarbon pipeline 104 either when no fluids are flowing through the pipeline 104 or when fluids (for example, drilling fluids, production fluids, other fluids) are flowing through the pipeline.

[0029] FIGS. 3A and 3B are examples of schematics of CP systems. FIG. 3A is an example of a schematic of a sacrificial CP system. In such systems, the surface of the structure to be protected from corrosion (for example, the hydrocarbon pipeline 104) is electrically connected to a sacrificial anode 302 using a conducting material, for example, a metallic conductor 304. The sacrificial anode 302 can be a mass of less noble metal buried or immersed with the hydrocarbon pipeline 104 in a common electrolyte.

[0030] FIG. 3B is an example of a schematic of an impressed current CP system. In such systems, the surface of the structure to be protected from corrosion (for example, the hydrocarbon pipeline 104) and a ground bed anode 312 are connected to a negative terminal and a positive terminal, respectively, of a direct current (DC) source 316 through metallic conductors 314. The ground bed anode 312

can include multiple anodes buried in the ground or impressed in the same soil or water as the pipeline 104. In such systems, current can flow from each anode in the ground bed anode 312 to the pipeline 104. Portions of the pipeline 104 that are uncoated or from which the coatings have worn off (for example, due to corrosion) can permit the current to pass through while the coated portions being dielectric media can prevent the flow of current. In some implementations, the impressed current CP system can include a rectifier with a positive terminal connected to multiple grounded anodes in series and the negative terminal connected to the hydrocarbon pipeline 104.

[0031] FIG. 4 is a flowchart of an example process 400 of determining current flowing through a hydrocarbon pipeline. At 402, a specified quantity of current is passed to a hydrocarbon pipeline. For example, a CP system can pass the specified quantity of current to the hydrocarbon pipeline 104. In implementations in which the CP system is a sacrificial system, current is passed to the hydrocarbon pipeline from the sacrificed anodes. At 404, reflected light passing through a fiber optic cable connected to the pipeline is monitored. For example, the fiber optic cable 110 is coiled around a length of the hydrocarbon pipeline 104. Light from a light generator 116 and reflected light in response to the generated light are passed through the fiber optic cable 110. A polarimeter 114 detects the reflected light, particularly, properties of the reflected light, for example, a reflection angle, a quantity of the reflected light or other properties.

[0032] At 406, the quantity of current flowing through the pipeline is determined based on the reflected light. For example, the signal processor 116 determines the quantity of current flowing through the pipeline based, in part, on a strength of a magnetic field created by the current flowing through the pipeline 104. The principle of fiber optic current measurement originated from the Faraday Effect, which relates the magnetic field being produced by an electric current and a reflection of a light signal traveling in a fiber optic cable. In some implementations, the polarimeter 114 can measure the light reflection angle. Based on the light reflection angle, the signal processor 116 can measure a polarization rotation angle according to Equation (1).

$$\theta = \mu_0 H I = VBI \quad (1)$$

[0033] In Equation (1), θ is a polarization rotation angle, μ is permeability of Faraday rotator material, V is Verdet constant, B is magnetic flux density and l is the length of interaction between magnetic flux density and light beam, for example, the length L of the pipeline 104. The magnetic flux density is related to the measured electrical current by Equation (2).

$$B = \mu_0 i$$

(2)

[0034] In Equation (2), i is the electrical current. The signal processor 116 can transmit the measured electrical current, for example, to a test station or other location at which the current is monitored.

[0035] FIG. 5 is a flowchart of an example process 500 of monitoring current from a CP system flowing through a hydrocarbon pipeline. The process 500 can be implemented to determine if a quantity of current being passed to the hydrocarbon pipeline 104 is sufficient to mitigate pipeline corrosion. At 502, current from a CP system is passed to the hydrocarbon pipeline, for example, the hydrocarbon pipeline 104, to mitigate corrosion in the pipeline. The fiber optic system can be connected to the hydrocarbon pipeline 104. At 504, a fiber optic cable is coiled around a length of the pipeline 104. The fiber optic system is then operated to pass light through the fiber optic cable and to receive reflected light. At 506, light is passed through the fiber optic cable. At 508, reflected light through the fiber optic cable is monitored. At 510, a quantity of current flowing through the hydrocarbon pipeline is determined based at least on the reflected light.

[0036] Implementing the steps above allows determining the quantity of current flowing through the pipeline at a time instant. At 512, the monitoring and determining steps are repeated for multiple successive time instants. At each time instant, a respective quantity of current flowing through the pipeline is determined. At 514, a current density of current flowing through the pipeline 104 is determined based on the currents determined at the multiple time instants.

[0037] At 516, the current density is compared with a threshold current density. The threshold density can depend on factors including the soil in which the hydrocarbon pipeline is buried and the coatings on the pipeline. For example, in the absence of coatings, the threshold current density can be about 20 mA/m². Depending

on the type of coatings (for example, tape wrap, coal tar epoxy, fusion bonded epoxy coating, polyethylene coating), the threshold current density can range between about 0.1 mA/m² and about 1.25 mA/m². The threshold current density can also depend on the soil resistivity measured in ohm.m. For example, for soil resistivity increasing
 5 from less than 10 ohm.m to greater to 1000 ohm.m, the threshold current density can decrease from about 20 mA/m² to about 1 mA/m². The threshold current density can also be determined based on a surface area to be protected as shown in Equation (3).

$$I = \frac{A \times C}{1000} \quad (3)$$

[0038] In Equation (3), I is the total current in Amperes, A is the surface area to
 10 be protected and C is the current density in mA/m².

[0039] If the threshold is satisfied (decision “YES” at check 518), then, at 522, the CP system is continued to operate to pass the same quantity of current to the hydrocarbon pipeline 104. If the threshold is not satisfied (decision “NO” at check 518), for example, the determined current density is less than the threshold density,
 15 then, at 520, the CP system is adjusted to pass a different quantity of current to the hydrocarbon pipeline 104. After either step 520 or step 522, the steps to determine the current density by monitoring and determining currents at different time instants are continued to determine that the current density continues to satisfy the threshold current density.

[0040] In some implementations, the fiber optic system described here can determine and provide current flowing through the hydrocarbon pipeline in real-time. In other words, instead of gathering current measurements over a duration and providing the measurements at the end of the duration, the fiber optic system can provide current or current density measurements (or both) at multiple time instants
 25 within the duration. In addition, a time interval between a determination of current or current density (or both) and output of the same by the signal processor, for example, to a test station or other receiving unit, can be very small (for example, of the order of micro- or nano-seconds). For example, the time interval can be as fast as the processing resources of the signal processor will allow the signal processor to operate.

[0041] Real-time knowledge of current flowing through the hydrocarbon pipeline or the current density (or both) can allow monitoring the condition of the CP
 30

system. Based on the knowledge, the current passed by the CP system to the hydrocarbon pipeline 104 can be maintained at or above industrially recommended current density values based on the soil types, pipeline coatings, or other conditions. Alternatively or in addition, maintenance and repair operations can be performed on the CP systems using the knowledge of current or current density. For example, in sacrificial CP systems, a decrease in current or current density over a period of time can indicate that the sacrificial anode needs to be replaced. Real-time knowledge of the decrease in current or current density measured using the fiber optic systems described here can enable a faster response to such maintenance and repair.

[0042] Thus, particular implementations of the subject matter have been described. Other implementations are within the scope of the following claims.

CLAIMS

1. A system comprising:
a cathodic protection system coupled to a hydrocarbon pipeline, the cathodic protection system configured to pass a current through the hydrocarbon pipeline to
5 control corrosion of the hydrocarbon pipeline;
a fiber optic system connected to the cathodic protection system, the fiber optic system configured to:
measure the current flowing through the hydrocarbon pipeline over
time, and
10 provide the measured current.
2. The system of claim 1, wherein the fiber optic system comprises:
a fiber optic cable connected to the hydrocarbon pipeline;
a light generator connected to the fiber optic cable, the light generator
15 configured to generate light to pass through the fiber optic cable;
a polarimeter connected to the fiber optic cable, the polarimeter configured to detect reflected light that passes through the fiber optic cable, the reflected light generated in response to a reflection of the generated light; and
a signal processor connected to the fiber optic cable, the light generator and the
20 polarimeter, the signal processor configured to determine a quantity of current flowing through the hydrocarbon pipeline at a time instant based at least on a magnetic field generated by the current flowing through the hydrocarbon pipeline and the reflection of the light passing through the fiber optic cable.
- 25 3. The system of claim 2, wherein the signal processor is configured to detect a plurality of quantities of current at a corresponding plurality of time instants.
4. The system of claim 3, wherein the signal processor is configured to:
determine a current density of the current flowed through the hydrocarbon
30 pipeline by the cathodic protection system; and
compare the determined current density with a threshold current density.

5. The system of claim 4, wherein, based on a result of the comparing, the signal processor is configured to determine that the current density satisfies the threshold current density.
- 5 6. The system of claim 4, wherein, based on a result of the comparing, the signal processor is configured to:
- determine that the current density does not satisfy the threshold current density;
- and
- cause the cathodic protection system to modify a specified current passed to the
- 10 hydrocarbon pipeline to modify the current density to satisfy the threshold current density.
7. The system of claim 2, wherein the fiber optic cable is coiled around a length of the hydrocarbon pipeline.
- 15 8. The system of claim 7, wherein the hydrocarbon pipeline is an underground hydrocarbon pipeline comprising:
- a first portion and a third portion positioned in aerated soil, and
- a second portion positioned in non-aerated soil and between the first portion
- 20 and the third portion,
- wherein the fiber optic cable is coiled around each of the first portion, the second portion and the third portion.
9. The system of claim 7, wherein the hydrocarbon pipeline is a horizontal drill string
- 25 in a horizontal wellbore drilling system.
10. The system of claim 1, wherein the cathodic protection system is configured to pass a specified current to the hydrocarbon pipeline and the fiber optic system is configured to detect the current flowing through the hydrocarbon pipeline over time
- 30 while hydrocarbons are flowing through the hydrocarbon pipeline.

11. A method comprising:

passing a specified quantity of current to an underground hydrocarbon pipeline to control external corrosion of the underground hydrocarbon pipeline, wherein a quantity of current flowing through the underground hydrocarbon pipeline is affected
5 by the external corrosion of the underground hydrocarbon pipeline;

monitoring reflected light passing through a fiber optic cable connected to the underground hydrocarbon pipeline, wherein the reflected light is modulated by a magnetic field produced by the quantity of current flowing through the underground hydrocarbon pipeline; and

10 determining, based on the monitored reflected light, the quantity of current flowing through the underground hydrocarbon pipeline.

12. The method of claim 11, wherein monitoring the reflected light passing through the fiber optic cable connected to the underground hydrocarbon pipeline comprises:

15 connecting the fiber optic cable to the underground hydrocarbon pipeline;

passing light generated by a light generator through the fiber optic cable;

detecting the reflected light that passes through the fiber optic cable, the reflected light generated in response to a reflection of the generated light; and

determining the quantity of the current flowing through the underground
20 hydrocarbon pipeline based at least on a magnetic field generated by the current flowing through the underground hydrocarbon pipeline and the reflection of the light passing through the fiber optic cable.

13. The method of claim 12, determining the quantity of the current flowing through
25 the underground hydrocarbon pipeline comprises determining a plurality of quantities of current flowing through the underground hydrocarbon pipeline at a corresponding plurality of time instants.

14. The method of claim 13, further comprising:

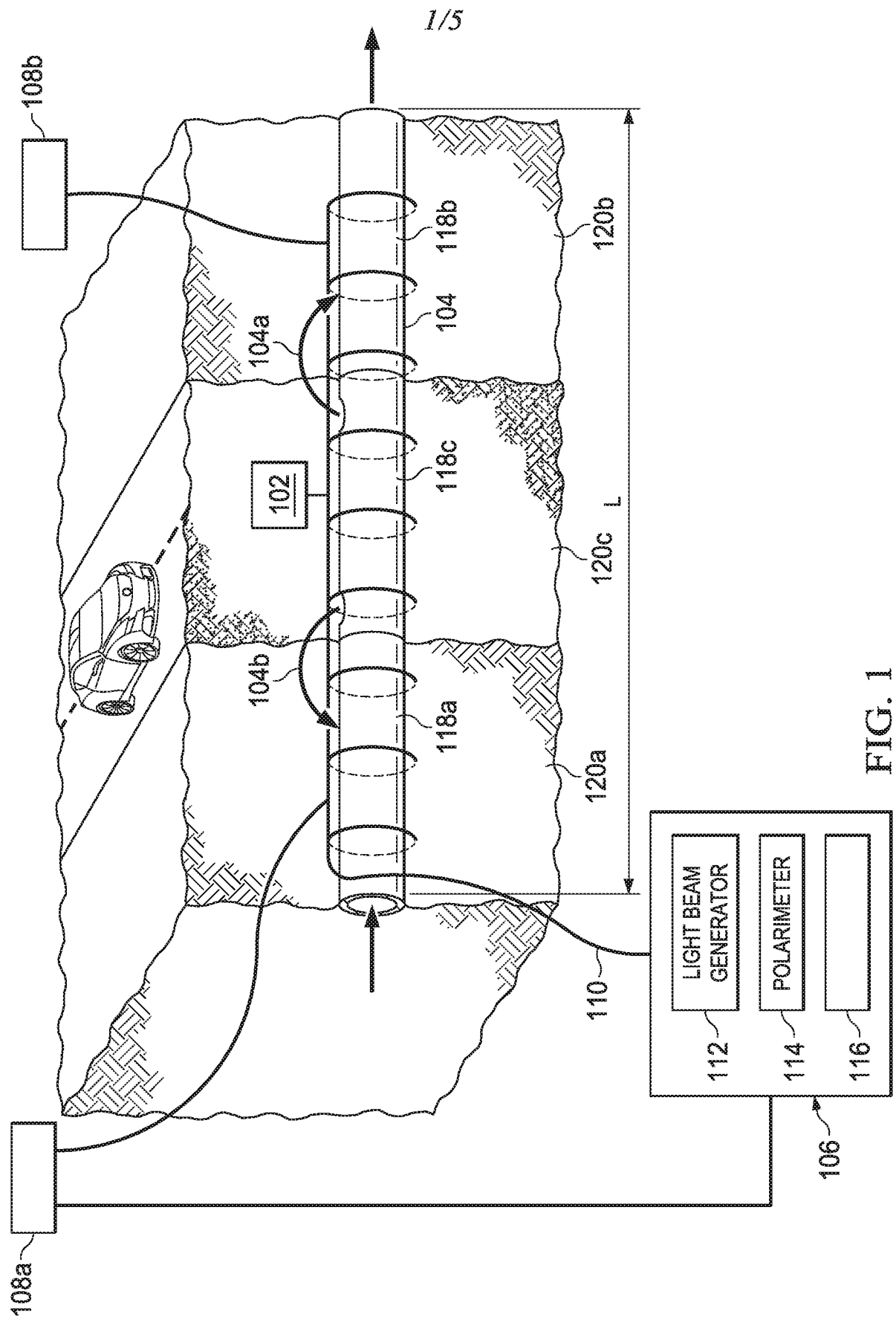
30 determining a current density of the current flowed through the underground hydrocarbon pipeline by the cathodic protection system; and

comparing the determined current density with a threshold current density.

15. The method of claim 14, wherein, based on a result of the comparing, determining that the current density satisfies the threshold current density.
16. The method of claim 14, wherein, based on a result of the comparing:
5 determining that the current density does not satisfy the threshold current density; and
 modifying the specified current passed to the underground hydrocarbon pipeline to satisfy the threshold current density.
- 10 17. The method of claim 12, wherein connecting the fiber optic cable to the underground hydrocarbon pipeline comprises coiling the fiber optic cable around a length of the underground hydrocarbon pipeline.
- 15 18. The method of claim 17, wherein the underground hydrocarbon pipeline comprises:
 a first portion and a third portion positioned in aerated soil, and
 a second portion positioned in non-aerated soil and between the first portion and the third portion,
 wherein the fiber optic cable is coiled around each of the first portion, the
20 second portion and the third portion.
19. The method of claim 17, wherein the underground hydrocarbon pipeline is a horizontal drill string in a horizontal wellbore drilling system.
- 25 20. A method comprising:
 coiling a fiber optic cable around an underground hydrocarbon pipeline connected to a cathodic protection system configured to pass a specified quantity of current to the underground hydrocarbon pipeline to control external corrosion of the underground hydrocarbon pipeline, wherein a quantity of current flowing through the
30 underground hydrocarbon pipeline is affected by the external corrosion of the underground hydrocarbon pipeline;
 passing light through the fiber optic cable;

monitoring reflected light passing through a fiber optic cable in response to the light, wherein the reflected light is modulated by the quantity of current flowing through the underground hydrocarbon pipeline; and

determining, based on the monitored reflected light, the quantity of current
5 flowing through the underground hydrocarbon pipeline.



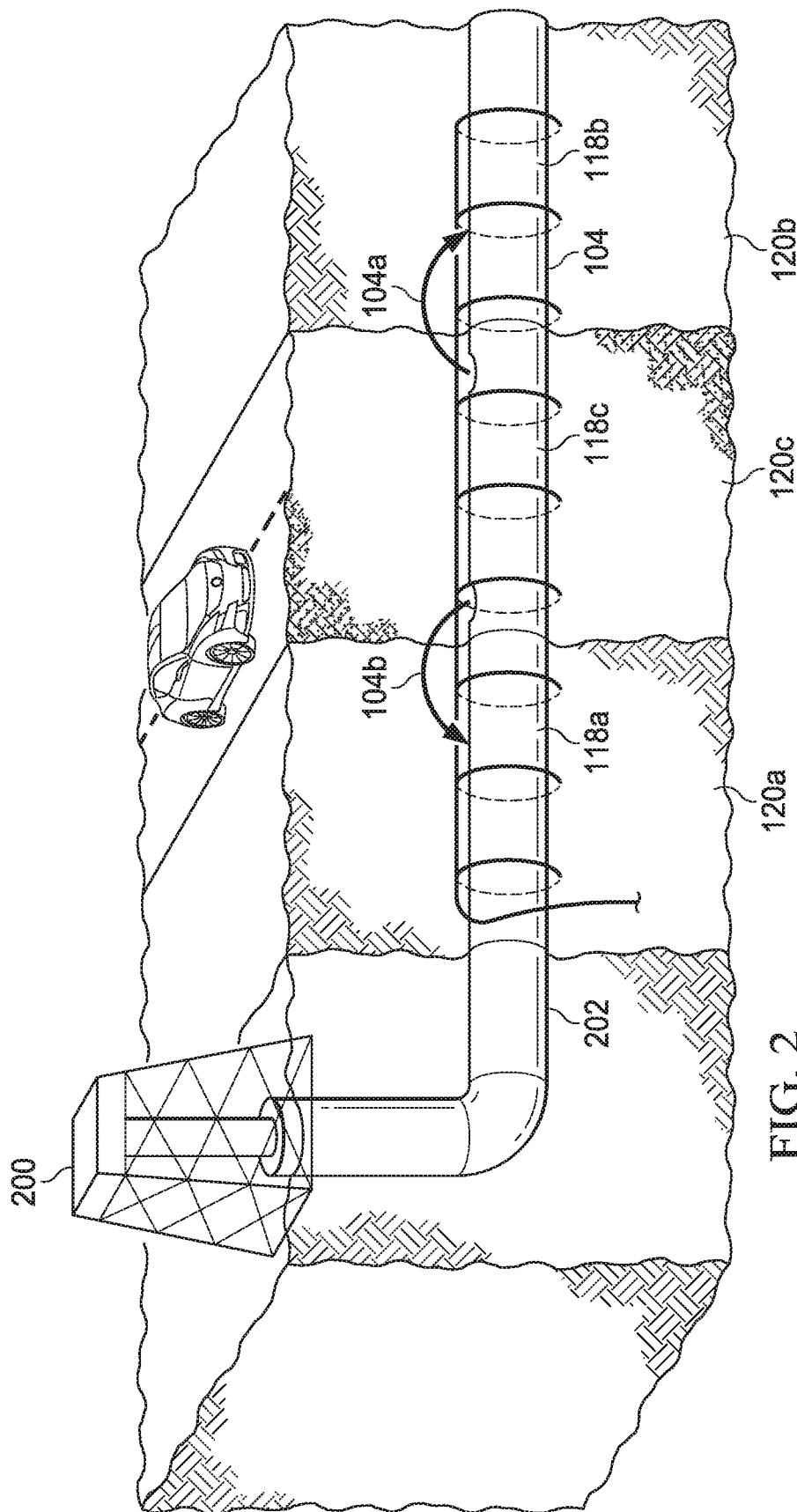


FIG. 2

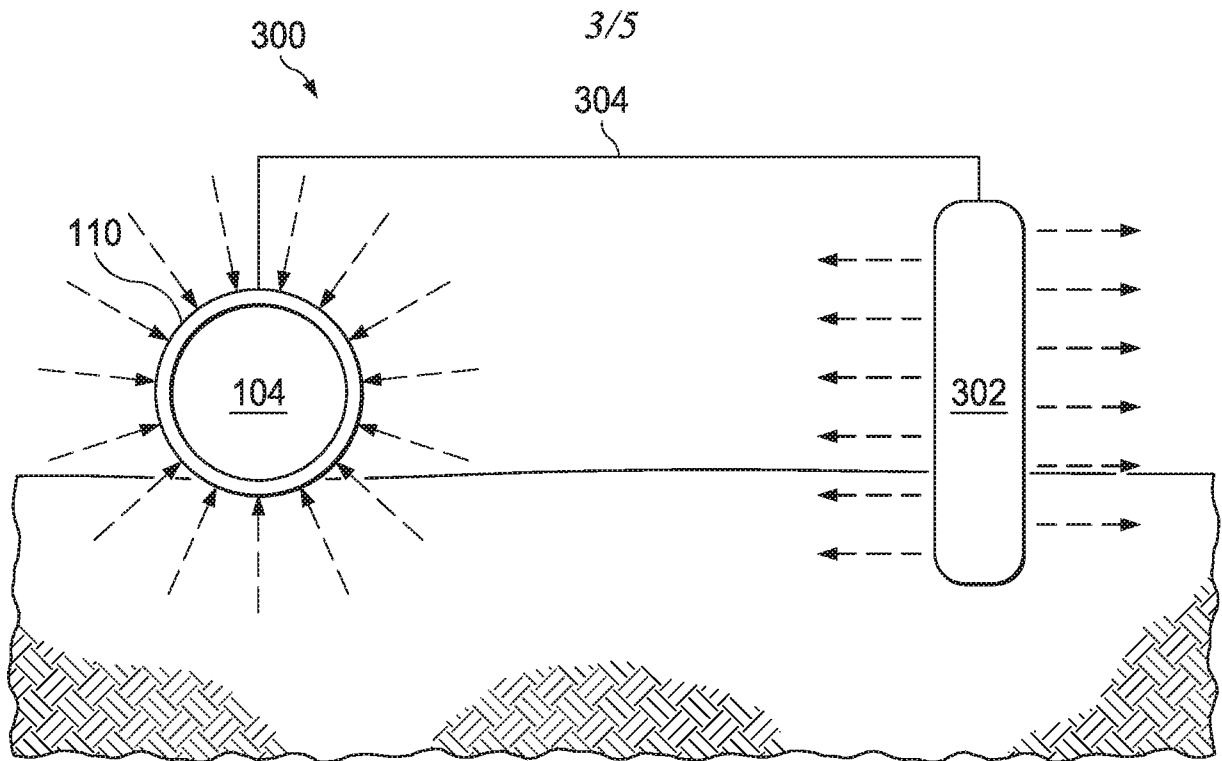


FIG. 3A

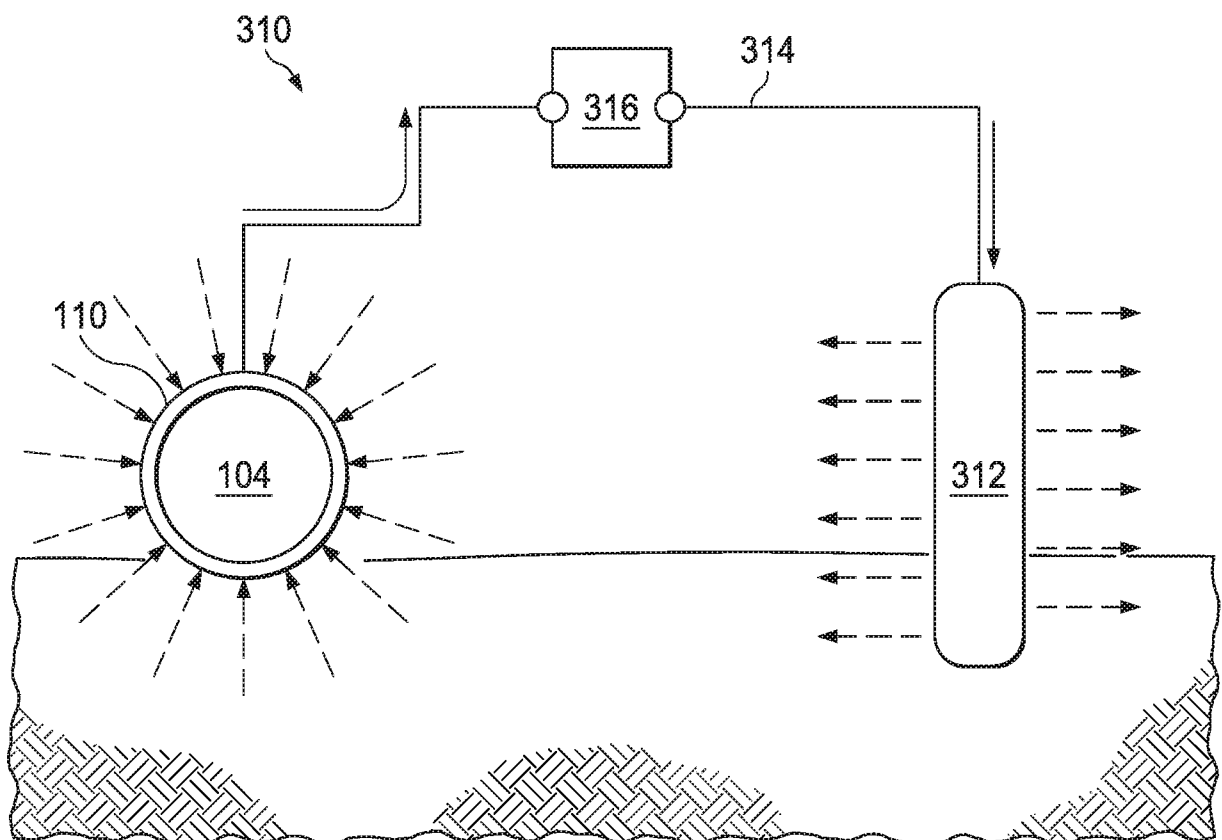


FIG. 3B

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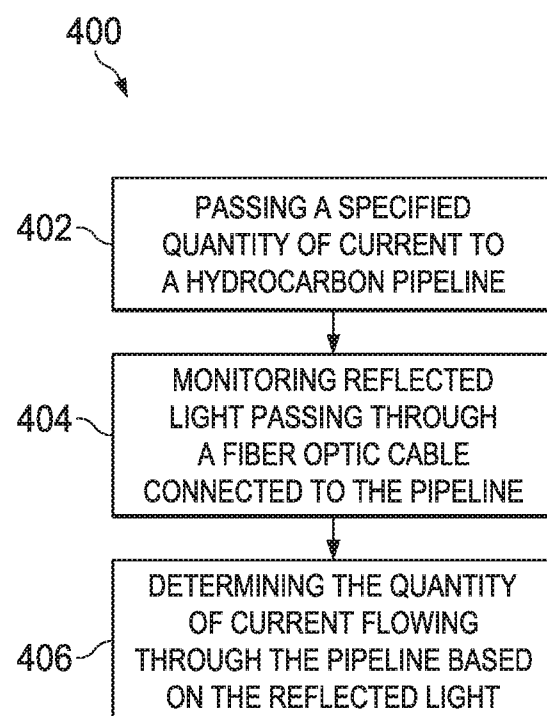


FIG. 4

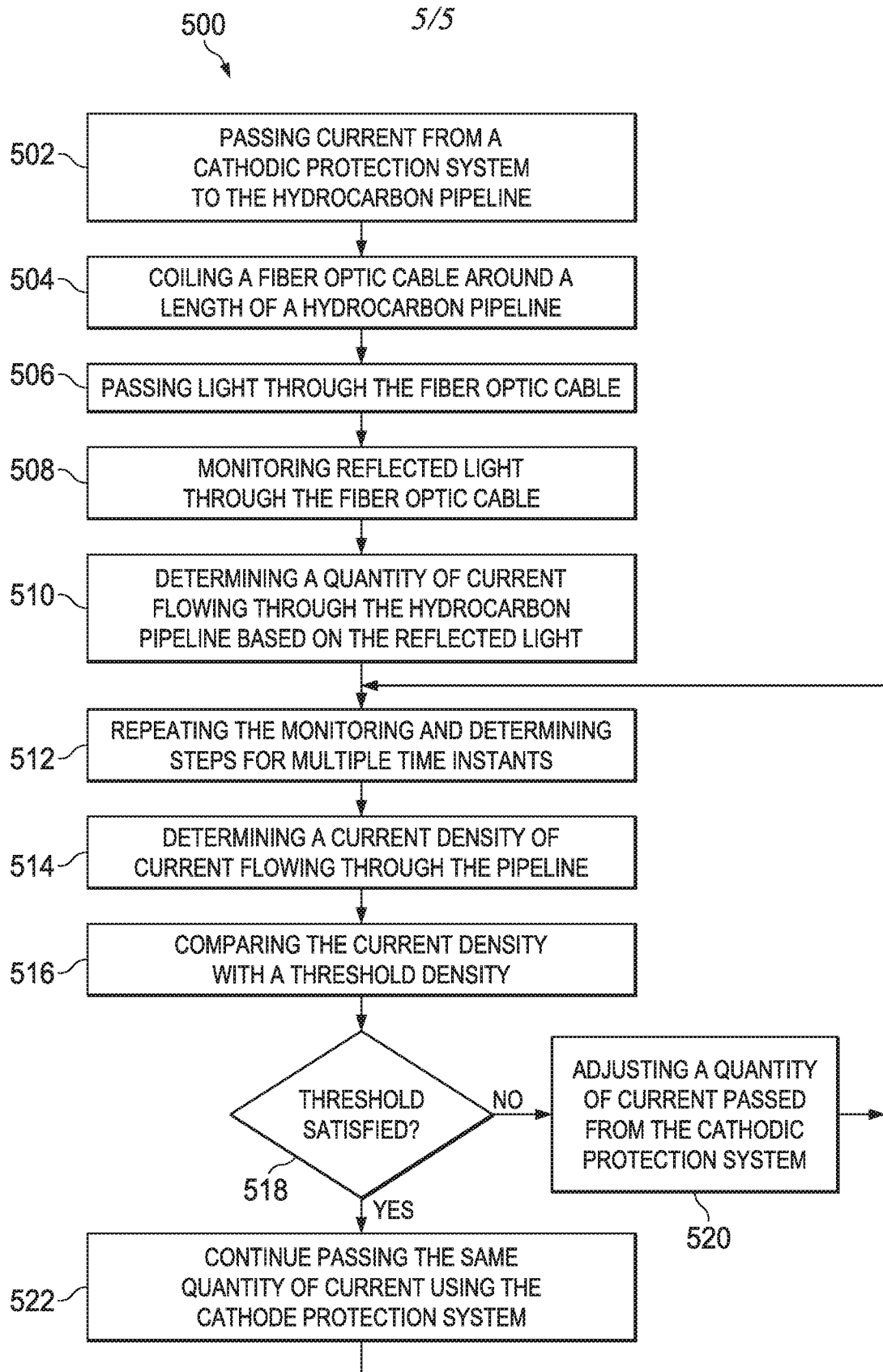


FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2017/012106

A. CLASSIFICATION OF SUBJECT MATTER

INV. C23F13/04 C23F13/22 F16L58/00 G01R33/032 G01N17/02
G01R15/24

ADD.

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)

C23F F16L G01R G01N

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 3 745 452 A (OSBURN J ET AL) 10 July 1973 (1973-07-10) claims 1, 2, 4 column 1, lines 6-11 -----	1-6, 8-16, 18, 19
Y	US 2009/250213 A1 (KALB FREDERIQUE [FR] ET AL) 8 October 2009 (2009-10-08) paragraphs [0044] - [0047] paragraph [0001] -----	1-6, 8-16, 18, 19
Y	US 2003/074162 A1 (FOURIE JULIUS W [US] ET AL) 17 April 2003 (2003-04-17) paragraph [0112] claims 1, 10, 11, 12, 21, 22, 25, 26 ----- -/--	4-6, 14-16



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

22 March 2017

Date of mailing of the international search report

06/04/2017

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GONZÁLEZ-MARTÍNEZ S ET AL: "Novel method for detecting weak magnetic fields at low frequencies", REVIEW OF SCIENTIFIC INSTRUMENTS, AIP, MELVILLE, NY, US, vol. 76, no. 6, 20 May 2005 (2005-05-20), pages 64701-064701, XP012079512, ISSN: 0034-6748 abstract I. INTRODUCTION; page 1 - page 2 IV. DISCUSSION; page 5	1-20
A	----- US 5 132 620 A (REMPT RAYMOND D [US]) 21 July 1992 (1992-07-21) claim 1	1-20
A	----- US 5 854 557 A (TIEFNIG EUGEN [US]) 29 December 1998 (1998-12-29) column 5, line 48 - column 8, line 4	1-20
A	----- US 3 284 702 A (OWNBY WARREN G) 8 November 1966 (1966-11-08) claim 1 -----	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

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