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CA 2606165 C 2014/07/29

(11)(21) **2 606 165**

(12) **BREVET CANADIEN**
CANADIAN PATENT

(13) **C**

(86) Date de dépôt PCT/PCT Filing Date: 2006/04/21

(87) Date publication PCT/PCT Publication Date: 2006/11/02

(45) Date de délivrance/Issue Date: 2014/07/29

(85) Entrée phase nationale/National Entry: 2007/10/17

(86) N° demande PCT/PCT Application No.: US 2006/014778

(87) N° publication PCT/PCT Publication No.: 2006/115945

(30) Priorité/Priority: 2005/04/22 (US60/674,081)

(51) Cl.Int./Int.Cl. *E21B 47/07* (2012.01), *E21B 47/12* (2012.01), *G01K 11/32* (2006.01)

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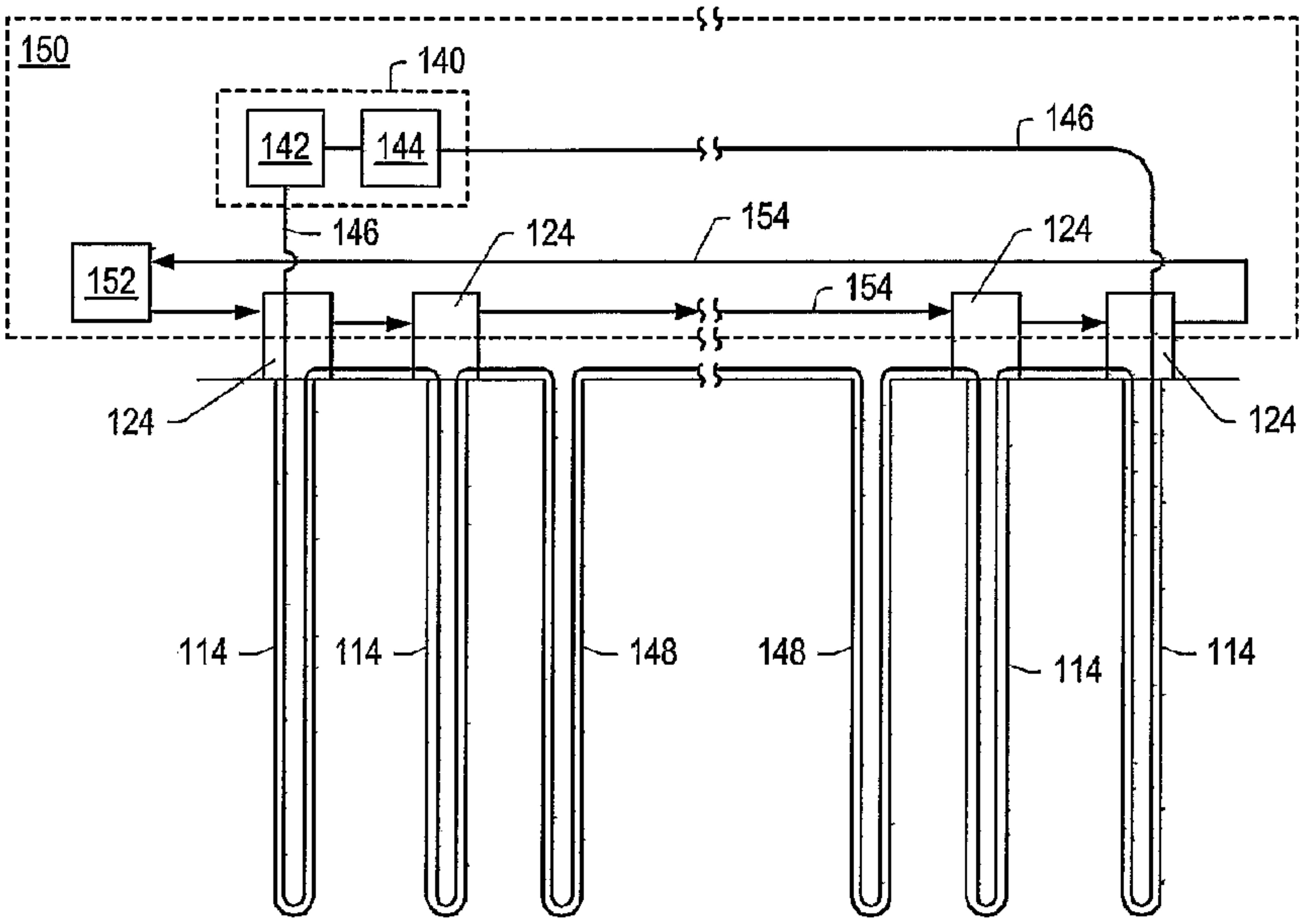
(54) Titre : SYSTEME DE SURVEILLANCE BASSE TEMPERATURE POUR BARRIERES SOUTERRAINES
(54) Title: LOW TEMPERATURE MONITORING SYSTEM FOR SUBSURFACE BARRIERS



(57) Abrégé/Abstract:

The invention provides a system for monitoring temperature of a subsurface low temperature zone, that includes a plurality of freeze wells (114) configured to form the low temperature zone; at least one monitor well; one or more lasers; a fiber optic cable (146) coupled to at least one laser (142), and an analyzer (144) coupled to the fiber optic cable. A portion of the fiber optic cable is positioned in at least one monitor well. At least one laser is configured to inject light pulses into at least one end of the fiber optic cable. The analyzer is configured to receive return signals from the light pulses. The invention also provides methods for monitoring temperature of a subsurface low temperature zone.

Canada *http://opic.gc.ca* · Ottawa/Gatineau K1A 0C9 · *http://cipo.gc.ca* OPIC CIPO

OPIC · CIPO 191

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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
2 November 2006 (02.11.2006)

PCT

(10) International Publication Number
WO 2006/115945 A1

(51) International Patent Classification:
E21B 47/06 (2006.01) ***G01K 11/32*** (2006.01)
E21B 47/12 (2006.01)

(21) International Application Number:
PCT/US2006/014778

(22) International Filing Date: 21 April 2006 (21.04.2006)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/674,081 22 April 2005 (22.04.2005) US

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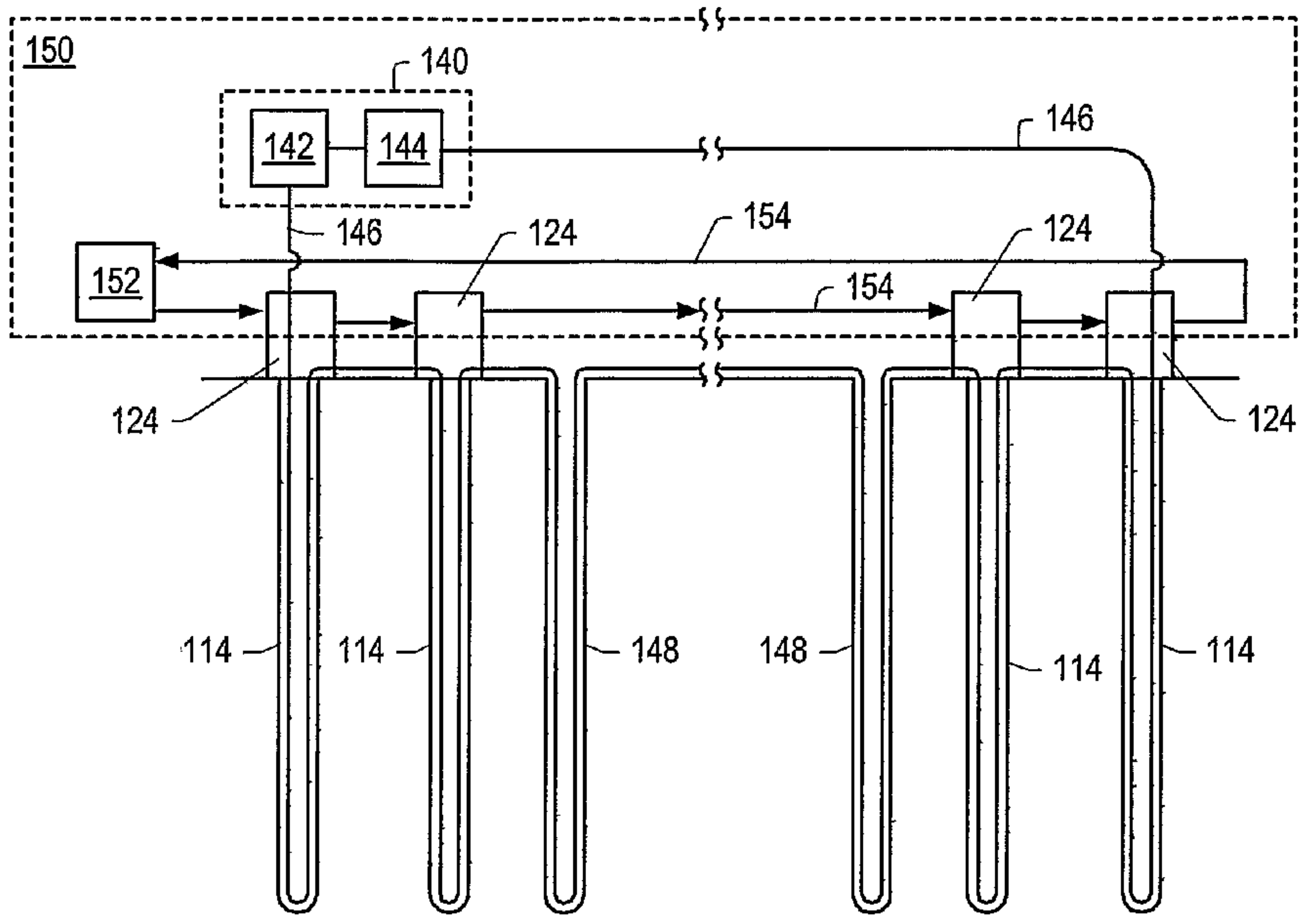
(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LC,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

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IS, IT, LT, LU, LV, MC, NL, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

[Continued on next page]

(54) Title: LOW TEMPERATURE MONITORING SYSTEM FOR SUBSURFACE BARRIERS



(57) Abstract: The invention provides a system for monitoring temperature of a subsurface low temperature zone, that includes a plurality of freeze wells (114) configured to form the low temperature zone; at least one monitor well; one or more lasers; a fiber optic cable (146) coupled to at least one laser (142), and an analyzer (144) coupled to the fiber optic cable. A portion of the fiber optic cable is positioned in at least one monitor well. At least one laser is configured to inject light pulses into at least one end of the fiber optic cable. The analyzer is configured to receive return signals from the light pulses. The invention also provides methods for monitoring temperature of a subsurface low temperature zone.

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LOW TEMPERATURE MONITORING SYSTEM FOR SUBSURFACE BARRIERS

BACKGROUND

1. Field of the Invention

The present invention relates generally to methods and systems for providing a low temperature barrier around at least a portion of a subsurface treatment area. The treatment area may be utilized for the production of hydrocarbons, hydrogen, and/or other products. Embodiments relate to the methods and systems for determining the temperature profile of the low temperature barrier.

2. Description of Related Art

In situ processes may be used to treat subsurface formations. During some in situ processes, fluids may be introduced or generated in the formation. Introduced or generated fluids may need to be contained in a treatment area to minimize or eliminate impact of the in situ process on adjacent areas. During some in situ processes, a barrier may be formed around all or a portion of the treatment area to inhibit migration fluids out of or into the treatment area.

A low temperature zone may be used to isolate selected areas of subsurface formation for many purposes. In some systems, ground is frozen to inhibit migration of fluids from a treatment area during soil remediation. U.S. Patent Nos. 4,860,544 to Krieg et al., 4,974,425 to Krieg et al.; 5,507,149 to Dash et al., 6,796,139 to Briley et al.; and 6,854,929 to Vinegar et al. describe systems for freezing ground.

To form a low temperature barrier, spaced apart wellbores may be formed in the formation where the barrier is to be formed. Piping may be placed in the wellbores. A low temperature heat transfer fluid may be circulated through the piping to reduce the temperature adjacent to the wellbores. The low temperature zone around the wellbores may expand outward. Eventually the low temperature zones produced by two adjacent wellbores merge. The temperature of the low temperature zones may be sufficiently low to freeze formation fluid so that a substantially impermeable barrier is formed. The wellbore spacing may be from 1 m to 3 m or more.

Wellbore spacing may be a function of a number of factors, including formation composition and properties, formation fluid and properties, time available for forming the barrier, and temperature and properties of the low temperature heat transfer fluid. In general, a very cold temperature of the low temperature heat transfer fluid allows for a larger spacing and/or for quicker formation of the barrier. A very cold temperature may be -20° C or less.

During formation of a low temperature zone, the temperature of the formation in and/or adjacent to freeze wells may indicate the progress of low temperature barrier formation. After completion of the barrier, the temperature of the formation in and/or adjacent to the freeze wells or in monitor wells adjacent to the freeze wells may indicate potential problem areas that could result in a breach of the barrier. It is desirable to have a system for monitoring the temperature in and/or adjacent to freeze wells in the formation.

SUMMARY

Embodiments described herein generally relate to systems and/or methods for treating a subsurface formation and/or monitoring temperature of a subsurface low temperature zone.

In some embodiments, the invention provides a system for monitoring temperature of a subsurface low temperature zone, that includes a plurality of freeze wells configured to form the low temperature zone; at least one monitor well; one or more lasers; a fiber optic cable coupled to at least one laser, wherein a portion of the fiber optic cable is positioned in at least one monitor well, and at least one laser is configured to inject light pulses into at least one end of the fiber optic cable; and an analyzer coupled to the fiber optic cable, the analyzer configured to receive return signals from the light pulses.

In one embodiment the invention provides a system for monitoring temperature of a subsurface low temperature zone, comprising: a plurality of freeze wells configured to form the low temperature zone; one or more lasers; a fiber optic cable coupled to at least one laser, wherein a portion of the fiber optic cable is positioned in at least one freeze well, and wherein at least one laser is configured to transmit light pulses into a first end of the fiber optic cable; and an analyzer coupled to the fiber optic cable, the analyzer configured to receive return signals from the light pulses.

The invention also provides in combination with the above described invention a computer in communication with the analyzer; and a formation refrigeration circulation system in communication with the computer, wherein the formation refrigeration circulation system is configured to supply refrigerant to the freeze wells and wherein the computer is configured to assess the temperature profile data communicated from the analyzer.

The invention also provides methods of monitoring temperature of a low temperature subsurface barrier using the one or more of the described inventions, that includes transmitting light through the fiber optic cable; and analyzing one or more returned signals from the fiber optic cable with an analyzer to assess a temperature profile along the fiber optic cable.

In further embodiments, features from specific embodiments may be combined with features from other embodiments. For example, features from one embodiment may be combined with features from any of the other embodiments.

In further embodiments, treating a subsurface formation is performed using any of the methods and/or systems described herein.

In further embodiments there is provided use of a system of the invention, for treating a subsurface formation, for example carrying out an in situ conversion process to yield hydrocarbon products and hydrogen.

In further embodiments, additional features may be added to the specific embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention may become apparent to those skilled in the art with the benefit of the following detailed description and upon reference to the accompanying drawings in which:

FIG. 1 shows a schematic view of an embodiment of a portion of an in situ conversion system for treating a hydrocarbon containing formation.

FIG. 2 depicts an embodiment of a freeze well for a circulated liquid refrigeration system, wherein a cutaway view of the freeze well is represented below ground surface.

FIG. 3 depicts a representation of a protective sleeve strapped to a canister of a freeze well.

FIG. 4 depicts a schematic representation of a fiber optic cable system used to monitor temperature in and near freeze wells.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and may herein be described in detail. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives.

DETAILED DESCRIPTION

The following description generally relates to systems and methods for treating hydrocarbons in formations. Formations may be treated using in situ conversion processes to yield hydrocarbon products, hydrogen, and other products. Freeze wells may be used to form a barrier around all or a portion of a formation being subjected to an in situ conversion process. A fiber optic temperature measurement system may be used to monitor the temperature of freeze wells and/or portions of the formation adjacent to the barrier formed by the freeze wells.

"Hydrocarbons" are generally defined as molecules formed primarily by carbon and hydrogen atoms. Hydrocarbons may also include other elements such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur. Hydrocarbons may be, but are not limited to, kerogen, bitumen, pyrobitumen, oils, natural mineral waxes, and asphaltites. Hydrocarbons may be located in or adjacent to mineral matrices in the earth. Matrices may include, but are not limited to, sedimentary rock, sands, silicilytes, carbonates, diatomites, and other porous media. "Hydrocarbon fluids" are fluids that include hydrocarbons. Hydrocarbon fluids may include, entrain, or be entrained in non-hydrocarbon fluids such as hydrogen, nitrogen, carbon monoxide, carbon dioxide, hydrogen sulfide, water, and ammonia.

A "formation" includes one or more hydrocarbon containing layers, one or more non-hydrocarbon layers, an overburden, and/or an underburden. The "overburden" and/or the "underburden" include one or more different types of impermeable materials. For example, overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate. In some embodiments of in situ conversion processes, the overburden and/or the underburden may include a hydrocarbon containing layer or hydrocarbon containing layers that are relatively impermeable and are not subjected to temperatures during in situ conversion processing that result in significant characteristic changes of the hydrocarbon containing layers of the overburden and/or the underburden. For example, the underburden may contain shale or mudstone, but the underburden is not allowed to heat to pyrolysis temperatures during the in situ conversion process. In some cases, the overburden and/or the underburden may be somewhat permeable.

"Formation fluids" refer to fluids present in a formation and may include pyrolyzation fluid, synthesis gas, mobilized hydrocarbon, and water (steam). Formation fluids may include hydrocarbon fluids as well as non-hydrocarbon fluids. The term "mobilized fluid" refers to fluids in a hydrocarbon containing formation that are able to flow as a result of thermal treatment of the formation. "Produced fluids" refer to formation fluids removed from the formation.

A "heat source" is any system for providing heat to at least a portion of a formation substantially by conductive and/or radiative heat transfer. For example, a heat source may include electric heaters such as an insulated conductor, an elongated member, and/or a conductor disposed in a conduit. A heat source may also include systems that generate heat by burning a fuel external to or in a formation. The systems may be surface burners, downhole gas burners, flameless distributed combustors, and natural distributed combustors. In some embodiments, heat provided to or generated in one or more heat sources may be supplied by other sources of energy. The other sources of energy may directly heat a formation, or the energy may be applied to a transfer medium that directly or indirectly heats the formation. It is to be understood that one or more heat sources that are applying heat to a formation may use different sources of energy. Thus, for example, for a given formation some heat sources may supply heat from electric resistance heaters, some heat sources may provide heat from combustion, and some heat sources may provide heat from one or more other energy sources (for example, chemical reactions, solar energy, wind energy, biomass, or other sources of renewable energy). A chemical reaction may include an exothermic reaction (for example, an oxidation reaction). A heat source may also include a heater that provides heat to a zone proximate and/or surrounding a heating location such as a heater well.

A "heater" is any system or heat source for generating heat in a well or a near wellbore region. Heaters may be, but are not limited to, electric heaters, burners, combustors that react with material in or produced from a formation, and/or combinations thereof.

An "in situ conversion process" refers to a process of heating a hydrocarbon containing formation from heat sources to raise the temperature of at least a portion of the formation above a pyrolysis temperature so that pyrolyzation fluid is produced in the formation.

The term "wellbore" refers to a hole in a formation made by drilling or insertion of a conduit into the formation. A wellbore may have a substantially circular cross section, or another cross-sectional shape. As used herein, the terms "well" and "opening," when referring to an opening in the formation may be used interchangeably with the term "wellbore."

"Pyrolysis" is the breaking of chemical bonds due to the application of heat. For example, pyrolysis may include transforming a compound into one or more other substances by heat alone. Heat may be transferred to a section of the formation to cause pyrolysis. In some formations, portions of the formation and/or other materials in the formation may promote pyrolysis through catalytic activity.

"Pyrolyzation fluid" or "pyrolysis products" refers to fluid produced substantially during pyrolysis of hydrocarbons. Fluid produced by pyrolysis reactions may mix with other fluids in a formation. The mixture would be considered pyrolyzation fluid or pyrolyzation product. As used herein, "pyrolysis zone" refers to a volume of a formation (for example, a relatively permeable formation such as a tar sands formation) that is reacted or reacting to form a pyrolyzation fluid.

"Thermal conductivity" is a property of a material that describes the rate at which heat flows, in steady state, between two surfaces of the material for a given temperature difference between the two surfaces.

Hydrocarbons or other desired products in a formation may be produced using various in situ processes. Some in situ processes that may be used to produce hydrocarbons or desired products are in situ conversion processes, steam flooding, fire flooding, steam-assisted gravity drainage, and solution mining. During some in situ processes, barriers may be needed or required. Barriers may inhibit fluid, such as formation water, from entering a treatment area. Barriers may also inhibit undesired exit of fluid from the treatment area. Inhibiting undesired exit of fluid from the treatment area may minimize or eliminate impact of the in situ process on areas adjacent to the treatment area.

FIG. 1 depicts a schematic view of an embodiment of a portion of in situ conversion system 100 for treating a hydrocarbon containing formation. In situ conversion system 100 may include barrier wells 102. Barrier wells 102 are used to form a barrier around a treatment area. The barrier inhibits fluid flow into and/or out of the treatment area. Barrier wells include, but are not limited to, dewatering wells, vacuum wells, capture wells, injection wells, grout wells, freeze wells, or combinations thereof. In the embodiment depicted in FIG. 1, barrier wells 102 are shown extending only along one side of heat sources 104, but the barrier wells typically encircle all heat sources 104 used, or to be used, to heat a treatment area of the formation.

Heat sources 104 are placed in at least a portion of the formation. Heat sources 104 may include heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 104 may also include other types of heaters. Heat sources 104 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heat sources 104 through supply lines 106. Supply lines 106 may be structurally different depending on the type of heat source or heat sources used to heat the formation. Supply lines 106 for heat sources may transmit electricity for electric heaters, may transport fuel for combustors, or may transport heat exchange fluid that is circulated in the formation.

Production wells 108 are used to remove formation fluid from the formation. In some embodiments, production well 108 may include one or more heat sources. A heat source in the production well may heat one or more portions of the formation at or near the production well. A heat source in a production well may inhibit condensation and reflux of formation fluid being removed from the formation.

Formation fluid produced from production wells 108 may be transported through collection piping 110 to treatment facilities 112. Formation fluids may also be produced from heat sources 104. For example, fluid may be produced from heat sources 104 to control pressure in the formation adjacent to the heat sources. Fluid produced from heat sources 104 may be transported through tubing or piping to collection piping 110 or the produced fluid may be transported through tubing or piping directly to treatment facilities 112. Treatment facilities 112 may include separation units, reaction units, upgrading units, fuel cells, turbines, storage vessels, and/or other systems and units for processing produced formation fluids. The treatment facilities may form transportation fuel from at least a portion of the hydrocarbons produced from the formation.

Some wellbores formed in the formation may be used to facilitate formation of a perimeter barrier around a treatment area. The perimeter barrier may be, but is not limited to, a low temperature or frozen barrier formed by freeze wells, dewatering wells, a grout wall formed in the formation, a sulfur cement barrier, a barrier formed by a gel produced in the formation, a barrier formed by precipitation of salts in the formation, a barrier formed by a polymerization reaction in the formation, and/or sheets driven into the formation. Heat sources, production wells, injection wells, dewatering wells, and/or monitoring wells may be installed in the treatment area defined by the barrier prior to, simultaneously with, or after installation of the barrier.

A low temperature zone around at least a portion of a treatment area may be formed by freeze wells. In an embodiment, refrigerant is circulated through freeze wells to form low temperature zones around each freeze well. The freeze wells are placed in the formation so that the low temperature zones overlap and form a low temperature zone around the treatment area. The low temperature zone established by freeze wells is maintained below the freezing temperature of aqueous fluid in the formation. Aqueous fluid entering the low temperature zone freezes and forms the frozen barrier. In other embodiments, the freeze barrier is formed by batch operated freeze wells. A cold fluid, such as liquid nitrogen, is introduced into the freeze wells to form low temperature zones around the freeze wells. The fluid is replenished as needed.

In some embodiments, two or more rows of freeze wells are located about all or a portion of the perimeter of the treatment area to form a thick interconnected low temperature zone. Thick low temperature zones may be formed adjacent to areas in the formation where there is a high flow rate of aqueous fluid in the formation. The thick barrier may ensure that breakthrough of the frozen barrier established by the freeze wells does not occur.

Vertically positioned freeze wells and/or horizontally positioned freeze wells may be positioned around sides of the treatment area. If the upper layer (the overburden) or the lower layer (the underburden) of the formation is likely to allow fluid flow into the treatment area or out of the treatment area, horizontally positioned freeze wells may be used to form an upper and/or a lower barrier for the treatment area. In some embodiments, an upper barrier and/or a lower barrier may not be necessary if the upper layer and/or the lower layer are at least substantially impermeable. If the upper freeze barrier is formed, portions of heat sources, production wells, injection wells, and/or dewatering wells that pass through the low temperature zone created by the freeze wells forming the upper freeze barrier wells may be insulated and/or heat traced so that the low temperature zone does not adversely affect the functioning of the heat sources, production wells, injection wells and/or dewatering wells passing through the low temperature zone.

Spacing between adjacent freeze wells may be a function of a number of different factors. The factors may include, but are not limited to, physical properties of formation material, type of refrigeration system, coldness and thermal properties of the refrigerant, flow rate of material into or out of the treatment area, time for forming the low temperature zone, and economic considerations. Consolidated or partially consolidated formation material may allow for a large separation distance between freeze wells. A separation distance between freeze wells in consolidated or partially consolidated formation material may be from 3 m to 20 m, 4 m to 15 m, or 5 m to 10 m. In an embodiment, the spacing between adjacent freeze wells is 5 m. Spacing between freeze wells in unconsolidated or substantially unconsolidated formation material, such as in tar sand, may need to be smaller than spacing in consolidated formation material. A separation distance between freeze wells in unconsolidated material may be from 1 m to 5 m.

Freeze wells may be placed in the formation so that there is minimal deviation in orientation of one freeze well relative to an adjacent freeze well. Excessive deviation may create a large separation distance between adjacent freeze wells that may not permit formation of an interconnected low temperature zone between the adjacent freeze wells. Factors that influence the manner in which freeze wells are inserted into the ground include, but are not limited to, freeze well insertion time, depth that the freeze wells are to be inserted, formation properties, desired well orientation, and economics.

Relatively low depth wellbores for freeze wells may be impacted and/or vibrationally inserted into some formations. Wellbores for freeze wells may be impacted and/or vibrationally inserted into formations to depths from 1 m to 100 m without excessive deviation in orientation of freeze wells relative to adjacent freeze wells in some types of formations.

Wellbores for freeze wells placed deep in the formation, or wellbores for freeze wells placed in formations with layers that are difficult to impact or vibrate a well through, may be placed in the formation by directional drilling and/or geosteering. Acoustic signals, electrical signals, magnetic signals, and/or other signals produced in a first wellbore may be used to guide drilling of adjacent wellbores so that desired spacing between adjacent wells is maintained. Tight control of the spacing between wellbores for freeze wells is an important factor in minimizing the time for completion of barrier formation.

After formation of the wellbore for the freeze well, the wellbore may be backflushed with water adjacent to the part of the formation that is to be reduced in temperature to form a portion of the freeze barrier. The water may displace drilling fluid remaining in the wellbore. The water may displace indigenous gas in cavities adjacent to the formation. In some embodiments, the wellbore is filled with water from a conduit up to the level of the overburden. In some embodiments, the wellbore is backflushed with water in sections. The wellbore maybe treated in sections having lengths of 6 m, 10 m, 14 m, 17 m, or greater. Pressure of the water in the wellbore is maintained below the fracture pressure of the formation. In some embodiments, the water, or a portion of the water is removed from the wellbore, and a freeze well is placed in the formation.

FIG. 2 depicts an embodiment of freeze well 114. Freeze well 114 may include canister 116, inlet conduit 118, spacers 120, and wellcap 122. Spacers 120 may position inlet conduit 118 in canister 116 so that an annular space is formed between the canister and the conduit. Spacers 120 may promote turbulent flow of refrigerant in the annular space between inlet conduit 118 and canister 116, but the spacers may also cause a significant fluid pressure drop. Turbulent fluid flow in the annular space may be promoted by roughening the inner surface of canister 116, by roughening the outer surface of inlet conduit 118, and/or by having a small cross-sectional area annular space that allows for high refrigerant velocity in the annular space. In some embodiments, spacers are not used. Wellhead 124 may suspend canister 116 in wellbore 126.

Formation refrigerant may flow through cold side conduit 128 from a refrigeration unit to inlet conduit 118 of freeze well 114. The formation refrigerant may flow through an annular space between inlet conduit 118 and canister 116 to warm side conduit 130. Heat may transfer from the formation to canister 116 and from the canister to the formation refrigerant in the annular space. Inlet conduit 118 may be insulated to inhibit heat transfer to the formation refrigerant during passage of the formation refrigerant into freeze well 114. In an embodiment, inlet conduit 118 is a high density polyethylene tube. At cold temperatures, some polymers may exhibit a large amount of thermal contraction. For example, a 260 m initial length of polyethylene conduit subjected to a temperature of -25 °C may contract by 6 m or more. If a high density polyethylene conduit, or other polymer conduit, is used, the large thermal contraction of the material must be taken into account in determining the final depth of the freeze well. For example, the freeze well may be drilled deeper than needed, and the conduit may be allowed to shrink back during use. In some embodiments, inlet conduit 118 is an insulated metal tube. In some embodiments, the insulation may be a polymer coating, such as, but not limited to, polyvinylchloride, high density polyethylene, and/or polystyrene.

Freeze well 114 may be introduced into the formation using a coiled tubing rig. In an embodiment, canister 116 and inlet conduit 118 are wound on a single reel. The coiled tubing rig introduces the canister and inlet conduit 118 into the formation. In an embodiment, canister 116 is wound on a first reel and inlet conduit 118 is wound on a second reel. The coiled tubing rig introduces canister 116 into the formation. Then, the coiled tubing rig is used to introduce inlet conduit 118 into the canister. In other embodiments, freeze well is assembled in sections at the wellbore site and introduced into the formation.

An insulated section of freeze well 114 may be placed adjacent to overburden 132. An uninsulated section of freeze well 114 may be placed adjacent to layer or layers 134 where a low temperature zone is to be formed. In some embodiments, uninsulated sections of the freeze wells may be positioned adjacent only to aquifers or other permeable portions of the formation that would allow fluid to flow into or out of the treatment area. Portions of the formation where uninsulated sections of the freeze wells are to be placed may be determined using analysis of cores and/or logging techniques.

In some embodiments, a protective sleeve is strapped to the canister as the canister is introduced into the formation. The protective sleeve may be in a u-shape. A turn-around sub near the end of the canister may accommodate the u-turn in the protective sleeve. A fiber may be inserted in the protective sleeve. FIG. 3 depicts a portion of canister 116 with protective sleeve 136 coupled to the canister by straps 138. Protective sleeve 136 may be stainless steel tubing or other tubing.

Various types of refrigeration systems may be used to form a low temperature zone. Determination of an appropriate refrigeration system may be based on many factors, including, but not limited to: type of freeze well; a distance between adjacent freeze wells; refrigerant; time frame in which to form a low temperature zone; depth of the low temperature zone; temperature differential to which the refrigerant will be subjected; chemical and physical properties of the refrigerant; environmental concerns related to potential refrigerant releases, leaks, or spills; economics; formation water flow in the formation; composition and properties of formation water, including the salinity of the formation water; and various properties of the formation such as thermal conductivity, thermal diffusivity, and heat capacity.

A circulated fluid refrigeration system may utilize a liquid refrigerant (formation refrigerant) that is circulated through freeze wells. Some of the desired properties for the formation refrigerant are: low working temperature, low viscosity at and near the working temperature, high density, high specific heat capacity, high thermal conductivity, low cost, low corrosiveness, and low toxicity. A low working temperature of the formation refrigerant allows a large low temperature zone to be established around a freeze well. The low working temperature of formation refrigerant should be -20 °C or lower. Formation refrigerants having low working temperatures of at least -60 °C may include aqua ammonia, potassium formate solutions such as Dynalene® HC-50 (Dynalene® Heat

Transfer Fluids (Whitehall, Pennsylvania, U.S.A.)) or FREEZIUM® (Kemira Chemicals (Helsinki, Finland)); silicone heat transfer fluids such as Syltherm XLT® (Dow Corning Corporation (Midland, Michigan, U.S.A.); hydrocarbon refrigerants such as propylene; and chlorofluorocarbons such as R-22. Aqua ammonia is a solution of ammonia and water with a weight percent of ammonia between 20% and 40%. Aqua ammonia has several properties and characteristics that make use of aqua ammonia as the formation refrigerant desirable. Such properties and characteristics include, but are not limited to, a very low freezing point, a low viscosity, ready availability, and low cost.

Formation refrigerant that is capable of being chilled below a freezing temperature of aqueous formation fluid may be used to form the low temperature zone around the treatment area. The following equation (the Sanger equation) may be used to model the time t_1 needed to form a frozen barrier of radius R around a freeze well having a surface temperature of T_s:

$$(1) \qquad t_1 = \frac{R^2 L_1}{4k_f v_s}\left(2\ln\frac{R}{r_o} - 1 + \frac{c_{vf} v_s}{L_1}\right)$$

in which:

$$L_1 = L\frac{a_r^2 - 1}{2\ln a_r} c_{vu} v_o$$

$$a_r = \frac{R_A}{R}.$$

In these equations, k_f is the thermal conductivity of the frozen material; c_{vf} and c_{vu} are the volumetric heat capacity of the frozen and unfrozen material, respectively; r_o is the radius of the freeze well; v_s is the temperature difference between the freeze well surface temperature T_s and the freezing point of water T_o; v_o is the temperature difference between the ambient ground temperature T_g and the freezing point of water T_o; L is the volumetric latent heat of freezing of the formation; R is the radius at the frozen-unfrozen interface; and R_A is a radius at which there is no influence from the refrigeration pipe. The Sanger equation may provide a conservative estimate of the time needed to form a frozen barrier of radius R because the equation does not take into consideration superposition of cooling from other freeze wells. The temperature of the formation refrigerant is an adjustable variable that may significantly affect the spacing between freeze wells.

EQN. 1 implies that a large low temperature zone may be formed by using a refrigerant having an initial temperature that is very low. The use of formation refrigerant having an initial cold temperature of -30 °C or lower is desirable. Formation refrigerants having initial temperatures warmer than -30 °C may also be used, but such formation refrigerants require longer times for the low temperature zones produced by individual freeze wells to connect. In addition, such formation refrigerants may require the use of closer freeze well spacings and/or more freeze wells.

The physical properties of the material used to construct the freeze wells may be a factor in the determination of the coldest temperature of the formation refrigerant used to form the low temperature zone around the treatment area. Carbon steel may be used as a construction material of freeze wells. ASTM A333 grade 6 steel alloys and ASTM A333 grade 3 steel alloys may be used for low temperature applications. ASTM A333 grade 6 steel alloys typically contain little or no nickel and have a low working temperature limit of -50 °C. ASTM A333 grade 3 steel alloys typically contain nickel and have a much colder low working temperature limit. The nickel in the ASTM A333 grade 3 alloy adds ductility at cold temperatures, but also significantly raises the cost of the metal.

In some embodiments, the coldest temperature of the refrigerant is from -35 °C to -55 °C, from -38 °C to -47 °C, or from -40 °C to -45 °C to allow for the use of ASTM A333 grade 6 steel alloys for construction of canisters for freeze wells. Stainless steels, such as 304 stainless steel, may be used to form freeze wells, but the cost of stainless steel is typically much more than the cost of ASTM A333 grade 6 steel alloy.

In some embodiments, the metal used to form the canisters of the freeze wells may be provided as pipe. In some embodiments, the metal used to form the canisters of the freeze wells may be provided in sheet form. The sheet metal may be longitudinally welded to form pipe and/or coiled tubing. Forming the canisters from sheet metal may improve the economics of the system by allowing for coiled tubing insulation and by reducing the equipment and manpower needed to form and install the canisters using pipe.

A refrigeration unit may be used to reduce the temperature of formation refrigerant to the low working temperature. In some embodiments, the refrigeration unit may utilize an ammonia vaporization cycle. Refrigeration units are available from Cool Man Inc. (Milwaukee, Wisconsin, U.S.A.), Gartner Refrigeration & Manufacturing (Minneapolis, Minnesota, U.S.A.), and other suppliers. In some embodiments, a cascading refrigeration system may be utilized with a first stage of ammonia and a second stage of carbon dioxide. The circulating refrigerant through the freeze wells may be 30% by weight ammonia in water (aqua ammonia). Alternatively, a single stage carbon dioxide refrigeration system may be used.

A temperature monitoring system may be installed in wellbores of freeze wells and/or in monitor wells adjacent to the freeze wells to monitor the temperature profile of the freeze wells and/or the low temperature zone established by the freeze wells. The monitoring system may be used to monitor progress of low temperature zone formation. The monitoring system may be used to determine the location of high temperature areas, potential breakthrough locations, or breakthrough locations after the low temperature zone has formed. Periodic monitoring of the temperature profile of the freeze wells and/or low temperature zone established by the freeze wells may allow additional cooling to be provided to potential trouble areas before breakthrough occurs. Additional cooling may be provided at or adjacent to breakthroughs and high temperature areas to ensure the integrity of the low temperature zone around the treatment area. Additional cooling may be provided by increasing refrigerant flow through selected freeze wells, installing an additional freeze well or freeze wells, and/or by providing a cryogenic fluid, such as liquid nitrogen, to the high temperature areas. Providing additional cooling to potential problem areas before breakthrough occurs may be more time efficient and cost efficient than sealing a breach, reheating a portion of the treatment area that has been cooled by influx of fluid, and/or remediating an area outside of the breached frozen barrier.

In some embodiments, a traveling thermocouple may be used to monitor the temperature profile of selected freeze wells or monitor wells. In some embodiments, the temperature monitoring system includes thermocouples placed at discrete locations in the wellbores of the freeze wells, in the freeze wells, and/or in the monitoring wells. In some embodiments, the temperature monitoring system comprises a fiber optic temperature monitoring system.

Fiber optic temperature monitoring systems are available from Sensornet (London, United Kingdom), Sensa (Houston, Texas, U.S.A.), Luna Energy (Blacksburg, Virginia, U.S.A.), Lios Technology GMBH (Cologne, Germany), Oxford Electronics Ltd. (Hampshire, United Kingdom), and Sabeus Sensor Systems (Calabasas, California, U.S.A.). The fiber optic temperature monitoring system includes a data system and one or more fiber optic cables. The data system includes one or more lasers for sending light to the fiber optic cable; and one or more computers, software and peripherals for receiving, analyzing, and outputting data. The data system may be coupled to one or more fiber optic cables.

A single fiber optic cable may be several kilometers long. The fiber optic cable may be installed in many freeze wells and/or monitor wells. In some embodiments, two fiber optic cables may be installed in each freeze well and/or monitor well. The two fiber optic cables may be coupled together. Using two fiber optic cables per well allows for compensation due to optical losses that occur in the wells and allows for better accuracy of measured temperature profiles.

A fiber of a fiber optic cable may be placed in a polymer tube. The polymer tube may be filled with a heat transfer fluid. The heat transfer fluid may be a gel or liquid that does not freeze at or above the temperature of formation refrigerant used to cool the formation. In some embodiments the heat transfer fluid in the polymer tube is the same as the formation refrigerant, for example, a fluid available from Dynalene® Heat Transfer Fluids or aqua ammonia. In some embodiments, the fiber is blown into the tube using the heat transfer fluid. Using the heat transfer fluid to insert the fiber into the polymer tube removes moisture from the polymer tube.

The polymer tube and fiber may be placed in the protective sleeve, such as ¼ inch 304 stainless steel tubing, to form the fiber optic cable. The protective sleeve may be prestressed to accommodate thermal contraction at low temperatures. The protective sleeve may be filled with the heat transfer fluid. In some embodiments, the polymer tube is blown into the protective sleeve with the heat transfer fluid. Using the heat transfer fluid to insert the polymer tube and fiber into the protective sleeve removes moisture from the protective sleeve. In some embodiments, two fibers are positioned in the same stainless steel tube. In some embodiments, the fiber is placed directly in the protective sleeve without being placed in a polymer tube.

In some embodiments, the fiber optic cable is strapped to the canister of the freeze well as the canister is inserted into the formation. The fiber optic cable may be coiled around the canister adjacent to the portions of the formation that are to be reduced to low temperature to form the low temperature zone. Coiling the fiber optic cable around the canister allows a long length of the fiber optic cable to be adjacent to areas that are to be reduced to low temperature. The long length allows for better resolution of the temperature profile for the areas to be reduced to low temperatures. In some embodiments, the fiber optic cable is placed in the canister of the freeze well.

FIG. 4 depicts a schematic representation of a fiber optic temperature monitoring system. Data system 140 includes laser 142 and analyzer 144. Laser 142 injects short, intense light pulses into fiber optic cable 146. Fiber optic cable 146 is positioned in a plurality of freeze wells 114 and monitor wells 148. Fiber optic cable 146 may be strapped to the canisters of the freeze wells as the canisters are installed in the formation. In some embodiments, the fiber optic cable is strapped to supports and inserted into the monitor wells. In some embodiments, the protective sleeve of the fiber optic cable may be suspended in the monitor wells without an additional support. Backscattering and reflection of light in fiber optic cable 146 may be measured as a function of time by analyzer 144 of the data system 140. Analysis of the backscattering and reflection of light data yields a temperature profile along the length of fiber optic cable 146.

In some embodiments, the data system is a double ended system. The data system may include one or more lasers that send light pulses into each end of the fiber optic cable. In some embodiments, the laser includes one laser. The laser sends pulses to each end of the fiber optic cable in an alternating manner. The return signals received by the data system allows for compensation of signal attenuation in the optical fiber.

In some embodiments, computer control system 150 is in communication with the fiber optic temperature monitoring system and the formation refrigeration circulation system. The formation refrigeration circulation system may include refrigeration system 152. Refrigeration system 152 sends chilled formation refrigerant to wellheads 124 of freeze wells 114 through piping 154. In some embodiments, the formation refrigerant passes down the inlet conduit of the freeze well and up through the annular space between the inlet conduit and the freeze well canister. The formation refrigerant then passes through the piping to the next freeze well.

Computer control system 150 may allow for automatic monitoring of the low temperature zone established by freeze wells 114. Computer control system 150 may periodically shut down the flow of formation refrigerant to a set of freeze wells for a given time. For example, computer control system 150 may shut down the flow of formation refrigerant to a specific set of freeze wells every 60 days for a period of two days and activate data system 140 to monitor the temperature profile near the shut down freeze wells. The temperature profile of the freeze wells with no formation refrigerant flow will begin to rise.

Computer control system 150 may monitor the rate of increase of temperature. If there is a problem area, the temperature profile near the problem area will show a greater rate of change than the temperature profile of adjacent areas. If a larger than expected temperature increase occurs at approximately the same depth location at or near two adjacent wells, the computer control system may signal that there is a problem to an operator of the system. The location of the problem area may be estimated/modeled/assessed by comparing the temperature increases between adjacent wells. For example, if the temperature increase in a first well is twice as large as the temperature increase in a second well, then the location of the problem area may be closer to the first well. Extra cooling and/or extra monitoring can be provided to problem areas. Extra cooling may be provided by increasing the flow of formation refrigerant to the problem area and/or by installing one or more additional freeze wells. If no problems are detected during the given time, the computer system restarts the flow of formation fluid to the specific set of freeze wells and begins a test of another set of freeze wells. Using computer control system 150 to monitor the low temperature zone established by freeze wells allows for problems to be detected and fixed before a breach of the barrier formed by the freeze wells occurs.

In some embodiments, the fiber optic temperature monitoring system utilizes Brillouin or Raman scattering systems. Such systems provide spatial resolution of 1 m and temperature resolution of 0.1 °C. With sufficient averaging and temperature calibration, the systems may be accurate to 0.5 °C.

In some embodiments, the fiber optic temperature monitoring system may be a Bragg system that uses a fiber optic cable etched with closely spaced Bragg gratings. The Bragg gratings may be formed in 1 foot increments along selected lengths of the fiber. Fibers with Bragg gratings are available from Luna Energy. The Bragg system only requires a single fiber optic cable to be placed in each well that is to be monitored. The Bragg system is able to measure the fiber temperature in a few seconds.

The fiber optic temperature monitoring system may be used to detect the location of a breach or a potential breach in a frozen barrier. The search for potential breaches may be performed at scheduled intervals, for example, every two or three months. To determine the location of the breach or potential breach, flow of formation refrigerant to the freeze wells of interest is stopped. In some embodiments, the flow of formation refrigerant to all of the freeze wells is stopped. The rise in the temperature profiles, as well as the rate of change of the temperature profiles, provided by the fiber optic temperature monitoring system for each freeze well can be used to determine the location of any breaches or hot spots in the low temperature zone maintained by the freeze wells. The temperature profile monitored by the fiber optic temperature monitoring system for the two freeze wells closest to the hot spot or fluid flow will show the quickest and greatest rise in temperature. A temperature change of a few degrees Centigrade in the temperature profiles of the freeze wells closest to a troubled area may be sufficient to isolate the location of the trouble area. The shut down time of flow of circulation fluid in the freeze wells of interest needed to detect breaches, potential breaches and hot spots may be on the order of a few hours or days, depending on the well spacing and the amount of fluid flow affecting the low temperature zone.

Fiber optic temperature monitoring systems may also be used to monitor temperatures in heated portions of the formation during in situ conversion processes. The fiber of a fiber optic cable used in the heated portion of the formation may be clad with a reflective material to facilitate retention of a signal or signals transmitted down the fiber. In some embodiments, the fiber is clad with gold, copper, nickel, aluminum and/or alloys thereof. The cladding maybe formed of a material that is able to withstand chemical and temperature conditions in the heated portion of the formation. For example, gold cladding may allow an optical sensor to be used up to temperatures of 700 °C. In some embodiments, the fiber is clad with aluminum. The fiber may be dipped in or run through a bath of liquid aluminum. The clad fiber may then be allowed to cool to secure the aluminum to the fiber. The gold or aluminum cladding may reduce hydrogen darkening of the optical fiber.

Further modifications and alternative embodiments of various aspects of the invention may be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as the presently preferred embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed, and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein. In addition, it is to be understood that features described herein independently may, in certain embodiments, be combined.

CLAIMS:

1. A system for monitoring temperature of a subsurface low temperature zone, comprising:

a plurality of freeze wells configured to form the low temperature zone;

one or more lasers;

a fiber optic cable coupled to at least one laser, wherein a portion of the fiber optic cable is positioned in at least one freeze well, and wherein at least one laser is configured to transmit light pulses into a first end of the fiber optic cable; and

an analyzer coupled to the fiber optic cable, the analyzer configured to receive return signals from the light pulses.

2. The system of claim 1, further comprising:

a computer control system in communication with the analyzer; and

a formation refrigeration circulation system in communication with the computer control system, wherein

the formation refrigeration circulation system is configured to supply refrigerant to the freeze wells and wherein the computer control system is configured to assess the temperature profile data communicated from the analyzer.

3. The system as claimed in claim 2, wherein the computer control system is configured to automatically adjust the flow of refrigerant to the freeze wells.

4. The system as claimed in any one of claims 1-3, wherein the fiber optic cable is positioned in at least one monitor well.

5. The system as claimed in any one of claims 1-4, wherein the fiber optic cable comprises a fiber and a metal tube, wherein the fiber is positioned in the metal tube.

6. The system as claimed in any one of claims 1-5, wherein a portion of the fiber optic cable adjacent to the low temperature zone is coiled.

7. The system as claimed in any one of claims 1-6, wherein at least a portion of the fiber optic cable includes Bragg gratings.

8. The system as claimed in any one of claims 1-7, wherein at least one laser is configured to transmit light pulses into a second end of the fiber optic cable.

9. The system as claimed in claim 8, wherein return signals from light transmitted into the second end of the fiber optic cable allows for compensation of signal attenuation.

10. The system as claimed in any one of claims 1-9, wherein one continuous fiber optic cable extends through a plurality of wellbores.

11. A method of monitoring temperature of a low temperature subsurface barrier using the system as claimed in any one of claims 1-10, comprising:

transmitting light through the fiber optic cable; and

analyzing one or more returned signals from the fiber optic cable with an analyzer to assess a temperature profile along the fiber optic cable.

12. The method as claimed in claim 11, wherein the analyzing comprises assessing the temperature profile in a freeze well used to form the subsurface low temperature barrier.

13. The method as claimed in claim 11 or 12, further comprising reporting the temperature profile.

14. The method as claimed in any one of claims 11-13, further comprising discontinuing circulation of the refrigerant.

15. The method as claimed in any one of claims 11-14, further comprising assessing temperature profiles of the wellbores based on information obtained from the fiber optic cables after circulation has ceased.

16. The method as claimed in any one of claims 11-15, further comprising determining the location of a breach by analysis of the temperature profiles.

17. The method as claimed in claim 16, further comprising reporting the location of the breach.

18. The method as claimed in any one of claims 11-17, further comprising heating a subsurface formation at least partially surrounded by the barrier.

19. The method as claimed in claim 18, further comprising producing fluids from the subsurface formation,

wherein the fluids comprise hydrocarbons.

20. The method as claimed in claim 19, further comprising producing transportation fuel from at least of a portion of the hydrocarbons.

21. A system for monitoring temperature of a subsurface low temperature zone, comprising:

a plurality of freeze wells configured to form the low temperature zone;

at least one monitor well;

one or more lasers;

a fiber optic cable coupled to at least one laser, wherein a portion of the fiber optic cable is positioned in at least one monitor well, and wherein at least one laser is configured to transmit light pulses into a first end of the fiber optic cable; and

an analyzer coupled to the fiber optic cable, the analyzer configured to receive return signals from the light pulses.

22. Use of the system as claimed in any one of claims 1-10 or 21, for carrying out an in situ conversion process to yield hydrocarbon products and hydrogen.

23. The use as claimed in claim 22, wherein said in situ conversion process comprises heating a hydrocarbon-containing formation bounded by said low temperature zone above a pyrolysis temperature to produce pyrolyzed fluid in the formation.

24. A method of treating a subsurface formation to produce hydrocarbons and hydrogen from the formation comprising:

bounding a subsurface hydrocarbon-containing formation with the low temperature zone of the system as claimed in any one of claims 1-10 or 21,

heating said formation within said low temperature zone,

monitoring temperature of the low temperature zone, and

recovering hydrocarbons and hydrogen from said formation.

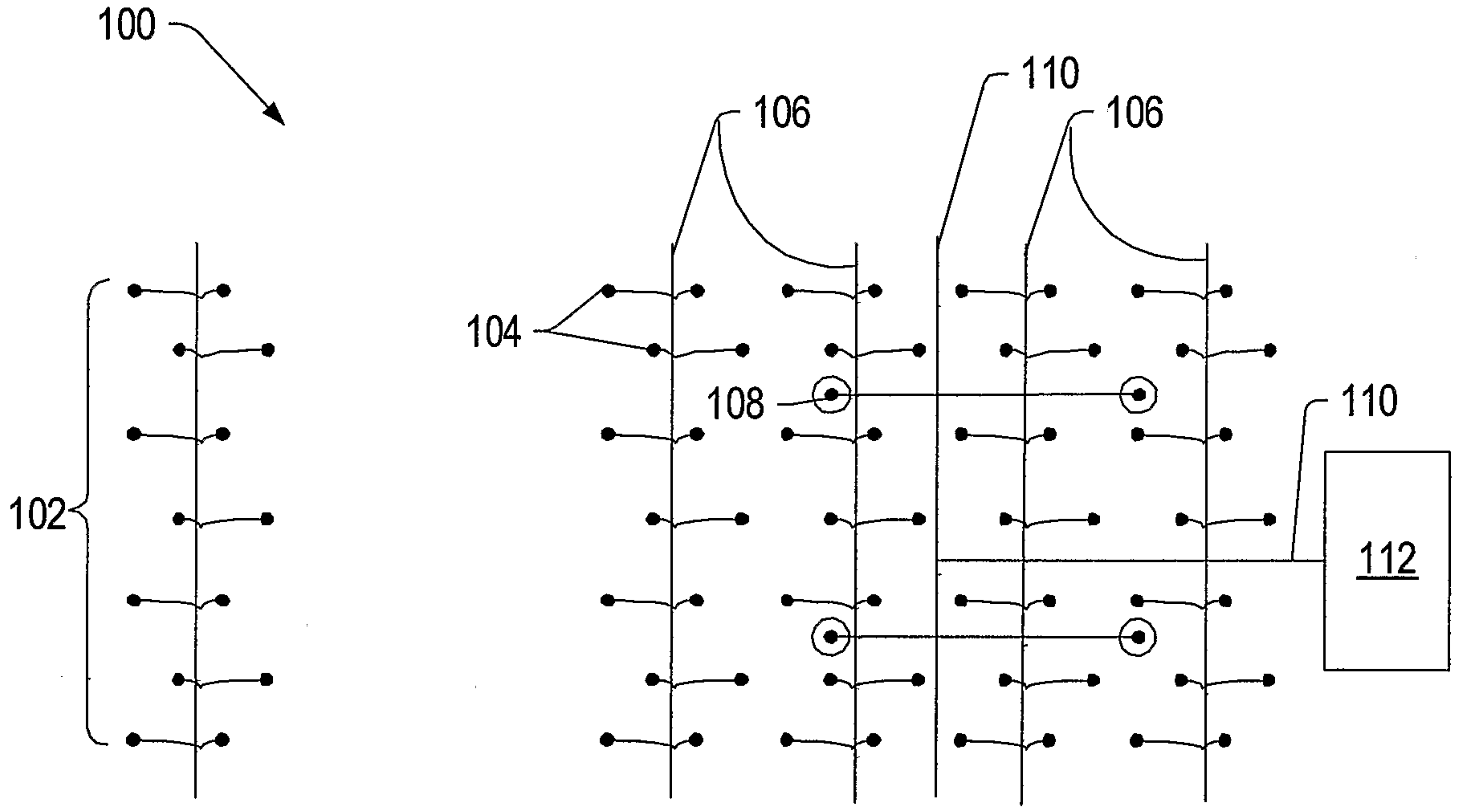

FIG. 1

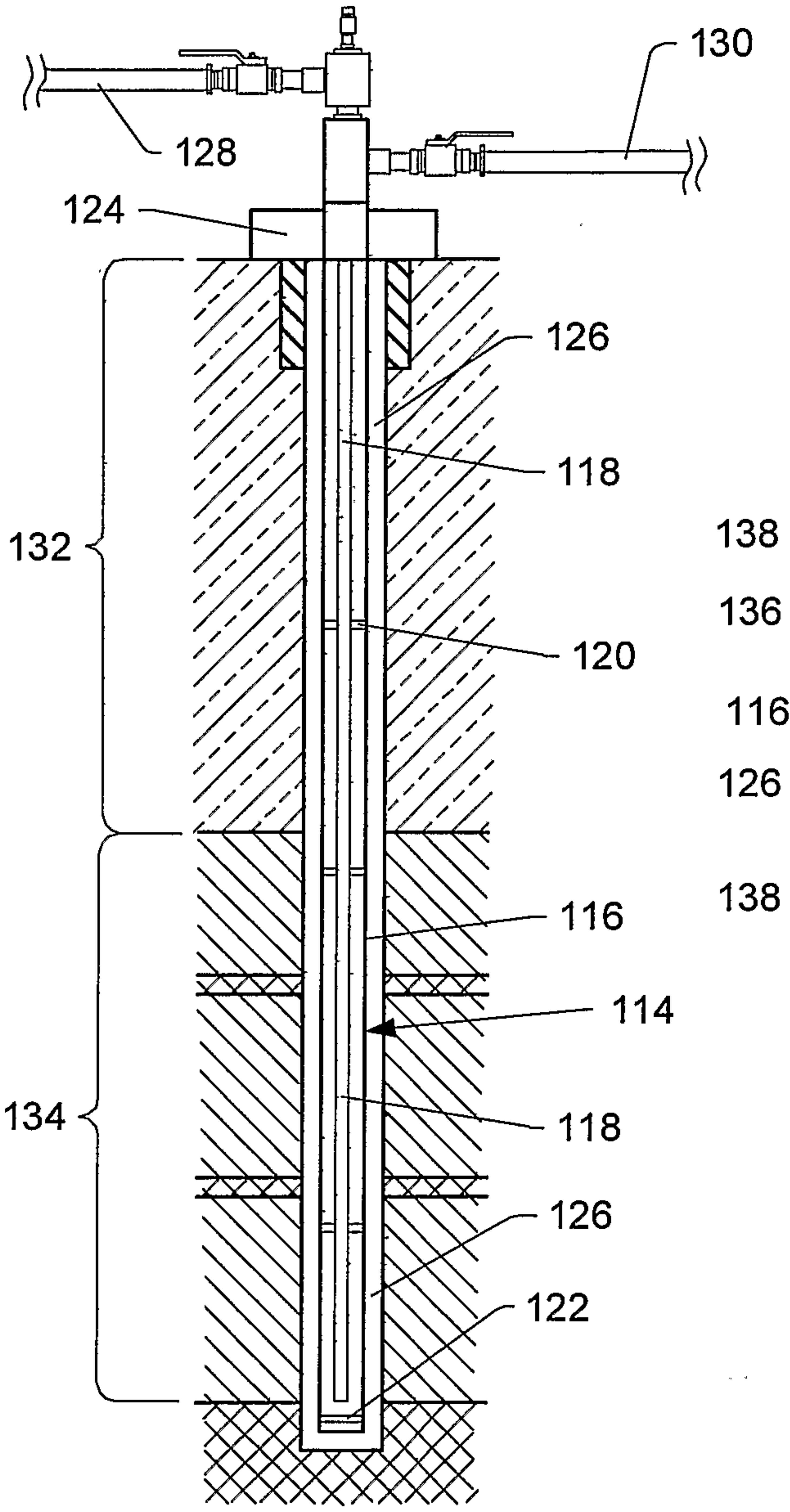
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FIG. 2

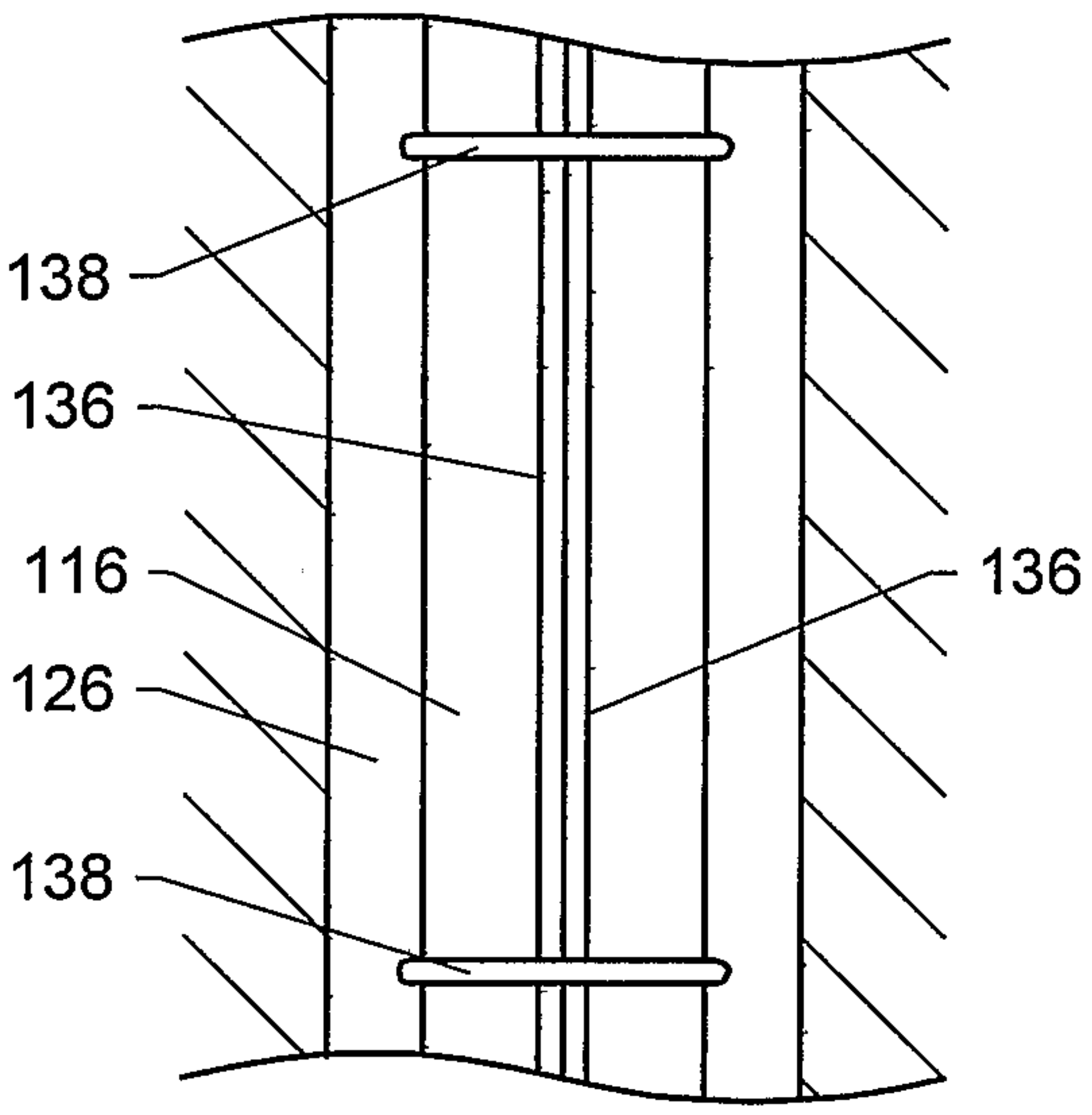
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FIG. 3

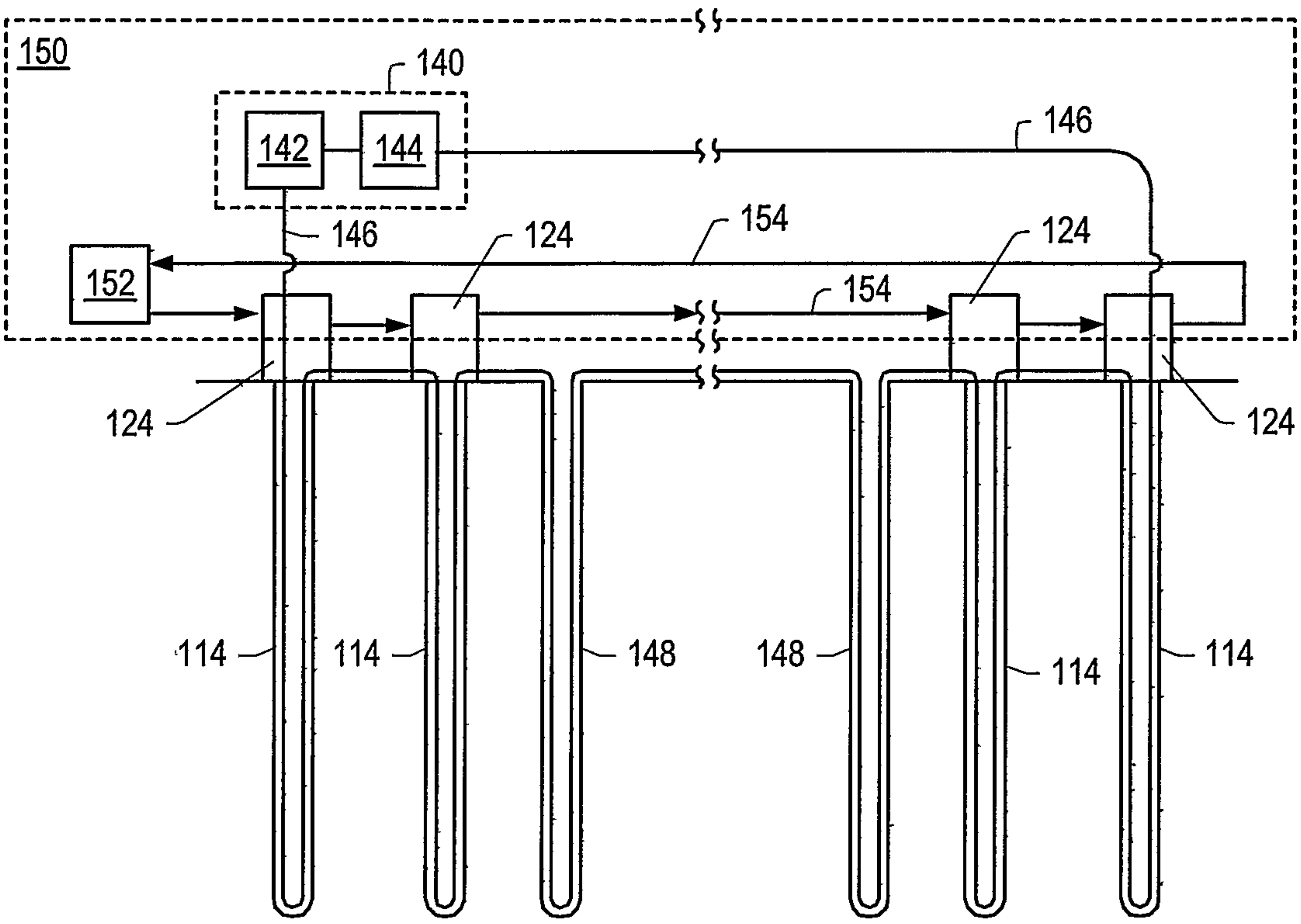
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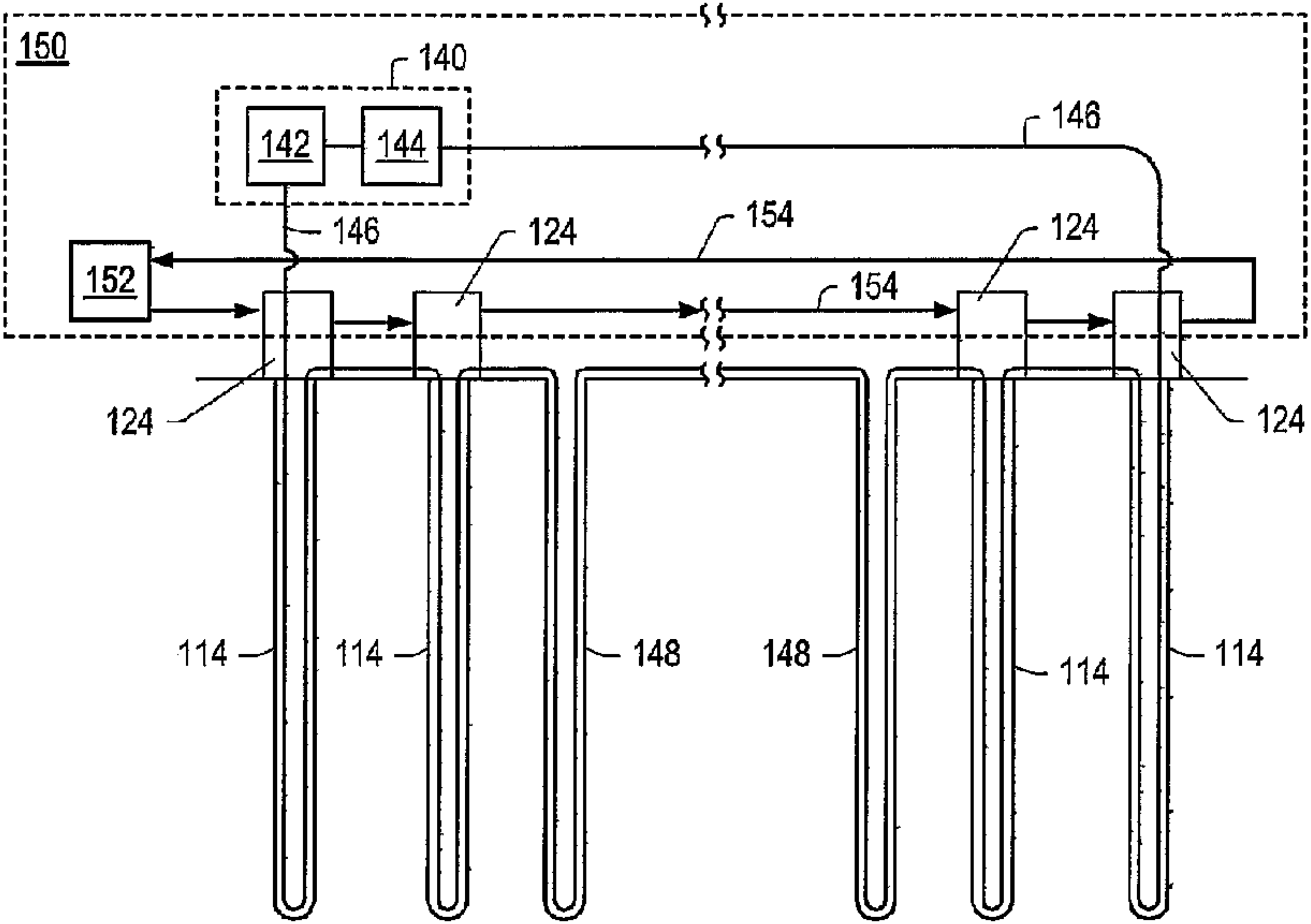
FIG. 4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