(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 2006/116131 A1

(51) **International Patent Classification:**
E21B 36/04 (2006.01) ***H01R 4/08*** (2006.01)

(21) **International Application Number:** PCT/US2006/015167

(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

(71) **Applicant** *(for all designated States except US)*: **SHELL OIL COMPANY** [US/US]; One Shell Plaza, P.o. Box 2463, Houston, Texas 77252-2463 (US).

(72) **Inventors; and**

(75) **Inventors/Applicants** *(for US only)*: **BASS, Ronald Marshall** [US/US]; 2028 Driscoll Street, Houston, Texas 77019 (US). **CARL, Frederick Gordon** [US/US]; 8406 Edgemoor Drive, Houston, Texas 77036 (US). **KELTNER, Thomas J.** [US/US]; 19139 Candle Trail, Spring, Texas 77388 (US). **KIM, Dong Sub** [US/US]; 3418 Mimosa Way, Sugar Land, Texas 77479 (US). **MASON, Stanley, Leroy** [US/US]; 1410 Creek Springs Drive, Allen, Texas 75002 (US). **STEGEMEIER, George Leo** [US/US]; 5819 Queensloch Drive, Houston, Texas 77096 (US). **VINEGAR, Harold J.** [US/US]; 4613 Laurel, Bellaire, Texas 77401 (US).

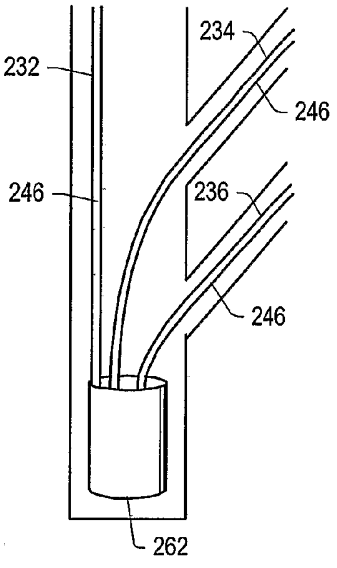
(74) **Agent: CHRISTENSEN, Del, S.**; SHELL OIL COMPANY, One Shell Plaza, P.o. Box 2463, Houston, 44 77252-2463 (US).

(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,

[Continued on next page]

(54) Title: SUBSURFACE CONNECTION METHODS FOR SUBSURFACE HEATERS



(57) **Abstract:** A system for heating a subsurface formation is described. The system includes a first elongated heater (246) in a first opening in the formation. The first elongated heater includes an exposed metal section in a portion of the first opening. The portion is below a layer of the formation to be heated (240) . The exposed metal section is exposed to the formation. A second elongated heater is located in a second opening in the formation. The second opening connects to the first opening at or near the portion of the first opening below the layer to be heated. At least a portion of an exposed metal section of the second elongated heater is electrically coupled to at least a portion of the exposed metal section of the first elongated heater in the portion of the first opening below the layer to be heated.

WO 2006/116131 A1

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*
- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

SUBSURFACE CONNECTION METHODS FOR SUBSURFACE HEATERS

BACKGROUND

1. Field of the Invention

The present invention relates generally to methods and systems for heating and production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations. Embodiments relate to systems and methods for coupling subsurface portions of heaters.

2. Description of Related Art

Hydrocarbons obtained from subterranean formations are often used as energy resources, as feedstocks, and as consumer products. Concerns over depletion of available hydrocarbon resources and concerns over declining overall quality of produced hydrocarbons have led to development of processes for more efficient recovery, processing and/or use of available hydrocarbon resources. In situ processes may be used to remove hydrocarbon materials from subterranean formations. Chemical and/or physical properties of hydrocarbon material in a subterranean formation may need to be changed to allow hydrocarbon material to be more easily removed from the subterranean formation. The chemical and physical changes may include in situ reactions that produce removable fluids, composition changes, solubility changes, density changes, phase changes, and/or viscosity changes of the hydrocarbon material in the formation. A fluid may be, but is not limited to, a gas, a liquid, an emulsion, a slurry, and/or a stream of solid particles that has flow characteristics similar to liquid flow.

Heaters may be placed in wellbores to heat a formation during an in situ process. Examples of in situ processes utilizing downhole heaters are illustrated in U.S. Patent Nos. 2,634,961 to Ljungstrom; 2,732,195 to Ljungstrom; 2,780,450 to Ljungstrom; 2,789,805 to Ljungstrom; 2,923,535 to Ljungstrom; and 4,886,118 to Van Meurs et al.

Application of heat to oil shale formations is described in U.S. Patent Nos. 2,923,535 to Ljungstrom and 4,886,118 to Van Meurs et al. Heat may be applied to the oil shale formation to pyrolyze kerogen in the oil shale formation. The heat may also fracture the formation to increase permeability of the formation. The increased permeability may allow formation fluid to travel to a production well where the fluid is removed from the oil shale formation. In some processes disclosed by Ljungstrom, for example, an oxygen containing gaseous medium is introduced to a permeable stratum, preferably while still hot from a preheating step, to initiate combustion.

A heat source may be used to heat a subterranean formation. Electric heaters may be used to heat the subterranean formation by radiation and/or conduction. An electric heater may resistively heat an element. U.S. Patent No. 2,548,360 to Germain describes an electric heating element placed in a viscous oil in a wellbore. The heater element heats and thins the oil to allow the oil to be pumped from the wellbore. U.S. Patent No. 4,716,960 to Eastlund et al. describes electrically heating tubing of a petroleum well by passing a relatively low voltage current through the tubing to prevent formation of solids. U.S. Patent No. 5,065,818 to Van Egmond describes an electric heating element that is cemented into a well borehole without a casing surrounding the heating element.

U.S. Patent No. 6,023,554 to Vinegar et al. describes an electric heating element that is positioned in a casing. The heating element generates radiant energy that heats the casing. A granular solid fill material may be placed between the casing and the formation. The casing may conductively heat the fill material, which in turn conductively heats the formation.

In some formations, it may be advantageous to electrically couple heaters in different openings below the surface of the formation. For example, heaters may be coupled in subsurface formations so that a first heater carries current downhole while a second heater acts a current return. In some cases, three heaters may be electrically coupled in the subsurface formation so that the heaters can be operated in a three-phase configuration. Thus, reliable systems and methods are needed for electrically coupling heaters in subsurface formations.

SUMMARY

Embodiments described herein generally relate to systems, methods, and heaters for treating a subsurface formation. Embodiments described herein also generally relate to heaters that have novel components therein. Such heaters can be obtained by using the systems and methods described herein.

In some embodiments, the invention provides a system for heating a subsurface formation, comprising: a first elongated heater in a first opening in the formation, wherein the first elongated heater includes an exposed metal section in a portion of the first opening, the portion being below a layer of the formation to be heated, and the exposed metal section being exposed to the formation; a second elongated heater in a second opening in the formation, wherein the second opening connects to the first opening at or near the portion of the first opening below the layer to be heated; and wherein at least a portion of an exposed metal section of the second elongated heater is electrically coupled to at least a portion of the exposed metal section of the first elongated heater in the portion of the first opening below the layer to be heated.

In certain embodiments, the invention provides one or more systems, methods, and/or heaters. In some embodiments, the systems, methods, and/or heaters are used for treating a subsurface formation.

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, systems, or heaters described herein.

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 depicts an illustration of stages of heating a hydrocarbon containing formation.

FIG. 2 shows a schematic view of an embodiment of a portion of an in situ conversion system for treating a hydrocarbon containing formation.

FIGS. 3, 4, and 5 depict cross-sectional representations of an embodiment of a temperature limited heater with an outer conductor having a ferromagnetic section and a non-ferromagnetic section.

FIGS. 6 and 6B depict cross-sectional representations of an embodiment of a temperature limited heater.

FIG. 7 depicts an embodiment of a temperature limited heater in which the support member provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor.

FIGS. 8 and 9 depict embodiments of temperature limited heaters in which the jacket provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor.

FIG. 10 depicts an embodiment of temperature limited heaters coupled together in a three-phase configuration.

FIG. 11 depicts an embodiment of two temperature limited heaters coupled together in a single contacting section.

FIG. 12 depicts an embodiment of two temperature limited heaters with legs coupled in a contacting section.

FIG. 13 depicts an embodiment of two temperature limited heaters with legs coupled in a contacting section with contact solution.

FIG. 14 depicts an embodiment of two temperature limited heaters with legs coupled without a contactor in a contacting section.

FIG. 15 depicts an embodiment of three heaters coupled in a three-phase configuration.

FIGS. 16 and 17 depict embodiments for coupling contacting elements of three legs of a heater.

FIG. 18 depicts an embodiment of a container with an initiator for melting the coupling material.

FIG. 19 depicts an embodiment of a container for coupling contacting elements with bulbs on the contacting elements.

FIG. 20 depicts an alternative embodiment for a container.

FIG. 21 depicts an alternative embodiment for coupling contacting elements of three legs of a heater.

FIG. 22 depicts a side view representation of an embodiment for coupling contacting elements using temperature limited heating elements.

FIG. 23 depicts a side view representation of an alternative embodiment for coupling contacting elements using temperature limited heating elements.

FIG. 24 depicts a side view representation of another alternative embodiment for coupling contacting elements using temperature limited heating elements.

FIG. 25 depicts a side view representation of an alternative embodiment for coupling contacting elements of three legs of a heater.

FIG. 26 depicts a top-view representation of the alternative embodiment for coupling contacting elements of three legs of a heater depicted in FIG. 25.

FIG. 27 depicts an embodiment of a contacting element with a brush contactor.

FIG. 28 depicts an embodiment for coupling contacting elements with brush contactors.

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 falling within the spirit and scope of the present invention as defined by the appended claims.

DETAILED DESCRIPTION

The following description generally relates to systems and methods for treating hydrocarbons in the formations. Such formations may be treated to yield hydrocarbon products, hydrogen, and other products.

"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.

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.

"Insulated conductor" refers to any elongated material that is able to conduct electricity and that is covered, in whole or in part, by an electrically insulating material.

An elongated member may be a bare metal heater or an exposed metal heater. "Bare metal" and "exposed metal" refer to metals that do not include a layer of electrical insulation, such as mineral insulation, that is designed to provide electrical insulation for the metal throughout an operating temperature range of the elongated member. Bare metal and exposed metal may encompass a metal that includes a corrosion inhibiter such as a naturally occurring oxidation layer, an applied oxidation layer, and/or a film. Bare metal and exposed metal include metals with polymeric or other types of electrical insulation that cannot retain electrical insulating properties at typical operating temperature of the elongated member. Such material may be placed on the metal and may be thermally degraded during use of the heater.

"Temperature limited heater" generally refers to a heater that regulates heat output (for example, reduces heat output) above a specified temperature without the use of external controls such as temperature controllers, power regulators, rectifiers, or other devices. Temperature limited heaters may be AC (alternating current) or modulated (for example, "chopped") DC (direct current) powered electrical resistance heaters.

"Curie temperature" is the temperature above which a ferromagnetic material loses all of its ferromagnetic properties. In addition to losing all of its ferromagnetic properties above the Curie temperature, the ferromagnetic material begins to lose its ferromagnetic properties when an increasing electrical current is passed through the ferromagnetic material.

"Time-varying current" refers to electrical current that produces skin effect electricity flow in a ferromagnetic conductor and has a magnitude that varies with time. Time-varying current includes both alternating current (AC) and modulated direct current (DC).

"Alternating current (AC)" refers to a time-varying current that reverses direction substantially sinusoidally. AC produces skin effect electricity flow in a ferromagnetic conductor.

"Modulated direct current (DC)" refers to any substantially non-sinusoidal time-varying current that produces skin effect electricity flow in a ferromagnetic conductor.

"Turndown ratio" for the temperature limited heater is the ratio of the highest AC or modulated DC resistance below the Curie temperature to the lowest resistance above the Curie temperature for a given current.

In the context of reduced heat output heating systems, apparatus, and methods, the term "automatically" means such systems, apparatus, and methods function in a certain way without the use of external control (for example, external controllers such as a controller with a temperature sensor and a feedback loop, PID controller, or predictive controller).

An "in situ conversion process" refers to a process of heating a hydrocarbon containing formation from heaters 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."

Hydrocarbons in formations may be treated in various ways to produce many different products. In certain embodiments, hydrocarbons in formations are treated in stages. FIG. 1 depicts an illustration of stages of heating the hydrocarbon containing formation. FIG. 1 also depicts an example of yield ("Y") in barrels of oil equivalent per ton (y axis) of formation fluids from the formation versus temperature ("T") of the heated formation in degrees Celsius (x axis).

Desorption of methane and vaporization of water occurs during stage 1 heating. Heating of the formation through stage 1 may be performed as quickly as possible. For example, when the hydrocarbon containing formation is initially heated, hydrocarbons in the formation desorb adsorbed methane. The desorbed methane may be produced from the formation. If the hydrocarbon containing formation is heated further, water in the hydrocarbon containing formation is vaporized. Water may occupy, in some hydrocarbon containing formations, between 10% and 50% of the pore volume in the formation. In other formations, water occupies larger or smaller portions of the pore volume. Water typically is vaporized in a formation between 160 °C and 285 °C at pressures of 600 kPa absolute to 7000 kPa absolute. In some embodiments, the vaporized water produces wettability changes in the formation and/or increased formation pressure. The wettability changes and/or increased pressure may affect pyrolysis reactions or other reactions in the formation. In certain embodiments, the vaporized water is produced from the formation. In other embodiments, the vaporized water is used for steam extraction and/or distillation in the formation or outside the formation. Removing the water from and increasing the pore volume in the formation increases the storage space for hydrocarbons in the pore volume.

In certain embodiments, after stage 1 heating, the formation is heated further, such that a temperature in the formation reaches (at least) an initial pyrolyzation temperature (such as a temperature at the lower end of the temperature range shown as stage 2). Hydrocarbons in the formation may be pyrolyzed throughout stage 2. A pyrolysis temperature range varies depending on the types of hydrocarbons in the formation. The pyrolysis temperature range may include temperatures between 250 °C and 900 °C. The pyrolysis temperature range for producing desired products may extend through only a portion of the total pyrolysis temperature range. In some embodiments, the pyrolysis temperature range for producing desired products may include temperatures between 250 °C and 400 °C or temperatures between 270 °C and 350 °C. If a temperature of hydrocarbons in the formation is slowly raised through the temperature range from 250 °C to 400 °C, production of pyrolysis products may be substantially complete when the temperature approaches 400 °C. Average temperature of the hydrocarbons may be raised at a rate of less than 5 °C per day, less than 2 °C per day, less than 1 °C per day, or less than 0.5 °C per day through the pyrolysis temperature range for producing desired products. Heating the hydrocarbon containing formation with a plurality of heat sources may establish thermal gradients around the heat sources that slowly raise the temperature of hydrocarbons in the formation through the pyrolysis temperature range.

The rate of temperature increase through the pyrolysis temperature range for desired products may affect the quality and quantity of the formation fluids produced from the hydrocarbon containing formation. Raising the temperature slowly through the pyrolysis temperature range for desired products may inhibit mobilization of large chain molecules in the formation. Raising the temperature slowly through the pyrolysis temperature range for desired products may limit reactions between mobilized hydrocarbons that produce undesired products. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the production of high quality, high API gravity hydrocarbons from the formation. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the removal of a large amount of the hydrocarbons present in the formation as hydrocarbon product.

In some in situ conversion embodiments, a portion of the formation is heated to a desired temperature instead of slowly heating the temperature through a temperature range. In some embodiments, the desired temperature is 300 °C, 325 °C, or 350 °C. Other temperatures may be selected as the desired temperature. Superposition of heat from heat sources allows the desired temperature to be relatively quickly and efficiently established in the formation. Energy input into the formation from the heat sources may be adjusted to maintain the temperature in the formation substantially at the desired temperature. The heated portion of the formation is maintained substantially at the desired temperature until pyrolysis declines such that production of desired formation fluids from the formation becomes uneconomical. Parts of the formation that are subjected to pyrolysis may include regions brought into a pyrolysis temperature range by heat transfer from only one heat source.

In certain embodiments, formation fluids including pyrolyzation fluids are produced from the formation. As the temperature of the formation increases, the amount of condensable hydrocarbons in the produced formation fluid may decrease. At high temperatures, the formation may produce mostly methane and/or hydrogen. If the hydrocarbon containing formation is heated throughout an entire pyrolysis range, the formation may produce only small amounts of hydrogen towards an upper limit of the pyrolysis range. After all of the available hydrogen is depleted, a minimal amount of fluid production from the formation will typically occur.

After pyrolysis of hydrocarbons, a large amount of carbon and some hydrogen may still be present in the formation. A significant portion of carbon remaining in the formation can be produced from the formation in the form of synthesis gas. Synthesis gas generation may take place during stage 3 heating depicted in FIG. 1. Stage 3 may include heating a hydrocarbon containing formation to a temperature sufficient to allow synthesis gas generation. For example, synthesis gas may be produced in a temperature range from 400 °C to 1200 °C, 500 °C to 1100 °C, or 550 °C to 1000 °C. The temperature of the heated portion of the formation when the synthesis gas generating fluid is introduced to the formation determines the composition of synthesis gas produced in the formation. The generated synthesis gas may be removed from the formation through a production well or production wells.

Total energy content of fluids produced from the hydrocarbon containing formation may stay relatively constant throughout pyrolysis and synthesis gas generation. During pyrolysis at relatively low formation temperatures, a significant portion of the produced fluid may be condensable hydrocarbons that have a high energy content. At higher pyrolysis temperatures, however, less of the formation fluid may include condensable hydrocarbons. More non-condensable formation fluids may be produced from the formation. Energy content per unit volume of the produced fluid may decline slightly during generation of predominantly non-condensable formation fluids. During synthesis gas generation, energy content per unit volume of produced synthesis gas declines significantly compared to energy content of pyrolyzation fluid. The volume of the produced synthesis gas, however, will in many instances increase substantially, thereby compensating for the decreased energy content.

FIG. 2 depicts a schematic view of an embodiment of a portion of the in situ conversion system for treating the hydrocarbon containing formation. The in situ conversion system may include barrier wells 200. Barrier wells 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 some embodiments, barrier wells 200 are dewatering wells. Dewatering wells may remove liquid water and/or inhibit liquid water from entering a portion of the formation to be heated, or to the formation being heated. In the embodiment depicted in FIG. 2, the barrier wells 200 are shown extending only along one side of heat sources 202, but the barrier wells typically encircle all heat sources 202 used, or to be used, to heat a treatment area of the formation.

Heat sources 202 are placed in at least a portion of the formation. Heat sources 202 may include heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 202 may also include other types of heaters. Heat sources 202 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heat sources 202 through supply lines 204. Supply lines 204 may be structurally different depending on the type of heat source or heat sources used to heat the formation. Supply lines 204 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 206 are used to remove formation fluid from the formation. In some embodiments, production well 206 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 206 may be transported through collection piping 208 to treatment facilities 210. Formation fluids may also be produced from heat sources 202. For example, fluid may be produced from heat sources 202 to control pressure in the formation adjacent to the heat sources. Fluid produced from heat sources 202 may be transported through tubing or piping to collection piping 208 or the produced fluid may be transported through tubing or piping directly to treatment facilities 210. Treatment facilities 210 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.

Temperature limited heaters may be in configurations and/or may include materials that provide automatic temperature limiting properties for the heater at certain temperatures. In certain embodiments, ferromagnetic materials are used in temperature limited heaters. Ferromagnetic material may self-limit temperature at or near the Curie temperature of the material to provide a reduced amount of heat at or near the Curie temperature when a time-varying current is applied to the material. In certain embodiments, the ferromagnetic material self-limits temperature of the temperature limited heater at a selected temperature that is approximately the Curie temperature. In certain embodiments, the selected temperature is within 35 °C, within 25 °C, within 20 °C, or within 10 °C of the Curie temperature. In certain embodiments, ferromagnetic materials are coupled with other materials (for example, highly conductive materials, high strength materials, corrosion resistant materials, or combinations thereof) to provide various electrical and/or mechanical properties. Some parts of the temperature limited heater may have a lower resistance (caused by different geometries and/or by using different ferromagnetic and/or non-ferromagnetic materials) than other parts of the temperature limited heater. Having parts of the temperature limited heater with various materials and/or dimensions allows for tailoring the desired heat output from each part of the heater.

Temperature limited heaters may be more reliable than other heaters. Temperature limited heaters may be less apt to break down or fail due to hot spots in the formation. In some embodiments, temperature limited heaters allow for substantially uniform heating of the formation. In some embodiments, temperature limited heaters are able to heat the formation more efficiently by operating at a higher average heat output along the entire length of the heater. The temperature limited heater operates at the higher average heat output along the entire length of the heater because power to the heater does not have to be reduced to the entire heater, as is the case with typical constant wattage heaters, if a temperature along any point of the heater exceeds, or is to exceed, a maximum operating temperature of the heater. Heat output from portions of a temperature limited heater approaching a Curie temperature of the heater automatically reduces without controlled adjustment of the time-varying current applied to the heater. The heat output automatically reduces due to changes in electrical properties (for example, electrical resistance) of portions of the temperature limited heater. Thus, more power is supplied by the temperature limited heater during a greater portion of a heating process.

In certain embodiments, the system including temperature limited heaters initially provides a first heat output and then provides a reduced (second heat output) heat output, near, at, or above the Curie temperature of an electrically resistive portion of the heater when the temperature limited heater is energized by a time-varying current. The first heat output is the heat output at temperatures below which the temperature limited heater begins to self-limit. In some embodiments, the first heat output is the heat output at a temperature 50 °C, 75 °C, 100 °C, or 125 °C below the Curie temperature of the ferromagnetic material in the temperature limited heater.

The temperature limited heater may be energized by time-varying current (alternating current or modulated direct current) supplied at the wellhead. The wellhead may include a power source and other components (for example, modulation components, transformers, and/or capacitors) used in supplying power to the temperature limited heater. The temperature limited heater may be one of many heaters used to heat a portion of the formation.

In certain embodiments, the temperature limited heater includes a conductor that operates as a skin effect or proximity effect heater when time-varying current is applied to the conductor. The skin effect limits the depth of current penetration into the interior of the conductor. For ferromagnetic materials, the skin effect is dominated by the magnetic permeability of the conductor. The relative magnetic permeability of ferromagnetic materials is typically between 10 and 1000 (for example, the relative magnetic permeability of ferromagnetic materials is typically at least 10 and may be at least 50, 100, 500, 1000 or greater). As the temperature of the ferromagnetic material is raised above the Curie temperature and/or as the applied electrical current is increased, the magnetic permeability of the ferromagnetic material decreases substantially and the skin depth expands rapidly (for example, the skin depth expands as the inverse square root of the magnetic permeability). The reduction in magnetic permeability results in a decrease in the AC or modulated DC resistance of the conductor near, at, or above the Curie temperature and/or as the applied electrical current is increased. When the temperature limited heater is powered by a substantially constant current source, portions of the heater that approach, reach, or are above the Curie temperature may have reduced heat dissipation. Sections of the temperature limited heater that are not at or near the

Curie temperature may be dominated by skin effect heating that allows the heater to have high heat dissipation due to a higher resistive load.

An advantage of using the temperature limited heater to heat hydrocarbons in the formation is that the conductor is chosen to have a Curie temperature in a desired range of temperature operation. Operation within the desired operating temperature range allows substantial heat injection into the formation while maintaining the temperature of the temperature limited heater, and other equipment, below design limit temperatures. Design limit temperatures are temperatures at which properties such as corrosion, creep, and/or deformation are adversely affected. The temperature limiting properties of the temperature limited heater inhibits overheating or burnout of the heater adjacent to low thermal conductivity "hot spots" in the formation. In some embodiments, the temperature limited heater is able to lower or control heat output and/or withstand heat at temperatures above 25 °C, 37 °C, 100 °C, 250 °C, 500 °C, 700 °C, 800 °C, 900 °C, or higher up to 1131 °C, depending on the materials used in the heater.

The temperature limited heater allows for more heat injection into the formation than constant wattage heaters because the energy input into the temperature limited heater does not have to be limited to accommodate low thermal conductivity regions adjacent to the heater. For example, in Green River oil shale there is a difference of at least a factor of 3 in the thermal conductivity of the lowest richness oil shale layers and the highest richness oil shale layers. When heating such a formation, substantially more heat is transferred to the formation with the temperature limited heater than with the conventional heater that is limited by the temperature at low thermal conductivity layers. The heat output along the entire length of the conventional heater needs to accommodate the low thermal conductivity layers so that the heater does not overheat at the low thermal conductivity layers and burn out. The heat output adjacent to the low thermal conductivity layers that are at high temperature will reduce for the temperature limited heater, but the remaining portions of the temperature limited heater that are not at high temperature will still provide high heat output. Because heaters for heating hydrocarbon formations typically have long lengths (for example, at least 10 m, 100 m, 300 m, at least 500 m, 1 km or more up to 10 km), the majority of the length of the temperature limited heater may be operating below the Curie temperature while only a few portions are at or near the Curie temperature of the temperature limited heater.

The use of temperature limited heaters allows for efficient transfer of heat to the formation. Efficient transfer of heat allows for reduction in time needed to heat the formation to a desired temperature. For example, in Green River oil shale, pyrolysis typically requires 9.5 years to 10 years of heating when using a 12 m heater well spacing with conventional constant wattage heaters. For the same heater spacing, temperature limited heaters may allow a larger average heat output while maintaining heater equipment temperatures below equipment design limit temperatures. Pyrolysis in the formation may occur at an earlier time with the larger average heat output provided by temperature limited heaters than the lower average heat output provided by constant wattage heaters. For example, in Green River oil shale, pyrolysis may occur in 5 years using temperature limited heaters with a 12 m heater well spacing. Temperature limited heaters counteract hot spots due to inaccurate well spacing or drilling where heater wells come too close together. In certain embodiments, temperature limited heaters allow for increased power output over time for heater wells that have been spaced too far apart, or limit power output for heater wells that are spaced too close together. Temperature limited heaters also supply more power in regions adjacent the overburden and underburden to compensate for temperature losses in these regions.

Temperature limited heaters may be advantageously used in many types of formations. For example, in tar sands formations or relatively permeable formations containing heavy hydrocarbons, temperature limited heaters may be used to provide a controllable low temperature output for reducing the viscosity of fluids, mobilizing fluids, and/or enhancing the radial flow of fluids at or near the wellbore or in the formation. Temperature limited heaters may be used to inhibit excess coke formation due to overheating of the near wellbore region of the formation.

The use of temperature limited heaters, in some embodiments, eliminates or reduces the need for expensive temperature control circuitry. For example, the use of temperature limited heaters eliminates or reduces the need to perform temperature logging and/or the need to use fixed thermocouples on the heaters to monitor potential overheating at hot spots.

In certain embodiments, the temperature limited heater is deformation tolerant. Localized movement of material in the wellbore may result in lateral stresses on the heater that could deform its shape. Locations along a length of the heater at which the wellbore approaches or closes on the heater may be hot spots where a standard heater overheats and has the potential to burn out. These hot spots may lower the yield strength and creep strength of the metal, allowing crushing or deformation of the heater. The temperature limited heater may be formed with S curves (or other non-linear shapes) that accommodate deformation of the temperature limited heater without causing failure of the heater.

In some embodiments, temperature limited heaters are more economical to manufacture or make than standard heaters. Typical ferromagnetic materials include iron, carbon steel, or ferritic stainless steel. Such materials are inexpensive as compared to nickel-based heating alloys (such as nichrome, Kanthal™ (Bulten-Kanthal AB, Sweden), and/or LOHM™ (Driver-Harris Company, Harrison, New Jersey, U.S.A.)) typically used in insulated conductor (mineral insulated cable) heaters. In one embodiment of the temperature limited heater, the temperature limited heater is manufactured in continuous lengths as an insulated conductor heater to lower costs and improve reliability.

In some embodiments, the temperature limited heater is placed in the heater well using a coiled tubing rig. A heater that can be coiled on a spool may be manufactured by using metal such as ferritic stainless steel (for example, 409 stainless steel) that is welded using electrical resistance welding (ERW). To form a heater section, a metal strip from a roll is passed through a first former where it is shaped into a tubular and then longitudinally welded using ERW. The tubular is passed through a second former where a conductive strip (for example, a copper strip) is applied, drawn down tightly on the tubular through a die, and longitudinally welded using ERW. A sheath may be formed by longitudinally welding a support material (for example, steel such as 347H or 347HH) over the conductive strip material. The support material may be a strip rolled over the conductive strip material. An overburden section of the heater may be formed in a similar manner. In certain embodiments, the overburden section uses a non-ferromagnetic material such as 304 stainless steel or 316 stainless steel instead of a ferromagnetic material. The heater section and overburden section may be coupled together using standard techniques such as butt welding using an orbital welder. In some embodiments, the overburden section material (the non-ferromagnetic material) may be pre-welded to the ferromagnetic material before rolling. The pre-welding may eliminate the need for a separate coupling step (for example, butt welding). In an embodiment, a flexible cable (for example, a furnace cable such as a MGT 1000 furnace cable) may be pulled through the center after forming the tubular heater. An end bushing on the flexible cable may be welded to the tubular heater to provide an electrical current return path. The tubular heater, including the flexible cable, may be coiled onto a spool before installation into a heater well. In an embodiment, the temperature limited heater is installed using the coiled tubing rig. The coiled tubing rig may place the temperature limited heater in a deformation resistant container in the formation. The deformation resistant container may be placed in the heater well using conventional methods.

The ferromagnetic alloy or ferromagnetic alloys used in the temperature limited heater determine the Curie temperature of the heater. Curie temperature data for various metals is listed in "American Institute of Physics Handbook," Second Edition, McGraw-Hill, pages 5-170 through 5-176. Ferromagnetic conductors may include one or more of the ferromagnetic elements (iron, cobalt, and nickel) and/or alloys of these elements. In some embodiments, ferromagnetic conductors include iron-chromium (Fe-Cr) alloys that contain tungsten (W) (for example, HCM12A and SAVE12 (Sumitomo Metals Co., Japan) and/or iron alloys that contain chromium (for example, Fe-Cr alloys, Fe-Cr-W alloys, Fe-Cr-V (vanadium) alloys, Fe-Cr-Nb (Niobium) alloys). Of the three main ferromagnetic elements, iron has a Curie temperature of 770 °C; cobalt (Co) has a Curie temperature of 1131 °C; and nickel has a Curie temperature of approximately 358 °C. An iron-cobalt alloy has a Curie temperature higher than the Curie temperature of iron. For example, iron-cobalt alloy with 2% by weight cobalt has a Curie temperature of 800 °C; iron-cobalt alloy with 12% by weight cobalt has a Curie temperature of 900 °C; and iron-cobalt alloy with 20% by weight cobalt has a Curie temperature of 950 °C. Iron-nickel alloy has a Curie temperature lower than the Curie temperature of iron. For example, iron-nickel alloy with 20% by weight nickel has a Curie temperature of 720 °C, and iron-nickel alloy with 60% by weight nickel has a Curie temperature of 560 °C.

Some non-ferromagnetic elements used as alloys raise the Curie temperature of iron. For example, an iron-vanadium alloy with 5.9% by weight vanadium has a Curie temperature of approximately 815 °C. Other non-ferromagnetic elements (for example, carbon, aluminum, copper, silicon, and/or chromium) may be alloyed with iron or other ferromagnetic materials to lower the Curie temperature. Non-ferromagnetic materials that raise the Curie temperature may be combined with non-ferromagnetic materials that lower the Curie temperature and alloyed with iron or other ferromagnetic materials to produce a material with a desired Curie temperature and other desired physical and/or chemical properties. In some embodiments, the Curie temperature material is a ferrite such as $NiFe_2O_4$. In other embodiments, the Curie temperature material is a binary compound such as $FeNi_3$ or Fe_3Al.

Certain embodiments of temperature limited heaters may include more than one ferromagnetic material. Such embodiments are within the scope of embodiments described herein if any conditions described herein apply to at least one of the ferromagnetic materials in the temperature limited heater.

Ferromagnetic properties generally decay as the Curie temperature is approached. The "Handbook of Electrical Heating for Industry" by C. James Erickson (IEEE Press, 1995) shows a typical curve for 1% carbon steel (steel with 1% carbon by weight). The loss of magnetic permeability starts at temperatures above 650 °C and tends to be complete when temperatures exceed 730 °C. Thus, the self-limiting temperature may be somewhat below the actual Curie temperature of the ferromagnetic conductor. The skin depth for current flow in 1% carbon steel is 0.132 cm at room temperature and increases to 0.445 cm at 720 °C. From 720 °C to 730 °C, the skin depth sharply increases to over 2.5 cm. Thus, a temperature limited heater embodiment using 1% carbon steel begins to self-limit between 650 °C and 730 °C.

Skin depth generally defines an effective penetration depth of time-varying current into the conductive material. In general, current density decreases exponentially with distance from an outer surface to the center along the radius of the conductor. The depth at which the current density is approximately $1/e$ of the surface current density is called the skin depth. For a solid cylindrical rod with a diameter much greater than the penetration depth, or for hollow cylinders with a wall thickness exceeding the penetration depth, the skin depth, δ, is:

(1) $\delta = 1981.5 * (\rho/(\mu * f))^{1/2}$;

in which: δ = skin depth in inches;

ρ = resistivity at operating temperature (ohm-cm);

μ = relative magnetic permeability; and

f = frequency (Hz).

EQN. 1 is obtained from "Handbook of Electrical Heating for Industry" by C. James Erickson (IEEE Press, 1995). For most metals, resistivity (ρ) increases with temperature. The relative magnetic permeability generally varies with temperature and with current. Additional equations may be used to assess the variance of magnetic permeability and/or skin depth on both temperature and/or current. The dependence of μ on current arises from the dependence of μ on the magnetic field.

Materials used in the temperature limited heater may be selected to provide a desired turndown ratio. Turndown ratios of at least 1.1:1, 2:1, 3:1, 4:1, 5:1, 10:1, 30:1, or 50:1 may be selected for temperature limited heaters. Larger turndown ratios may also be used. A selected turndown ratio may depend on a number of factors including, but not limited to, the type of formation in which the temperature limited heater is located (for example, a higher turndown ratio may be used for an oil shale formation with large variations in thermal conductivity between rich and lean oil shale layers) and/or a temperature limit of materials used in the wellbore (for example, temperature limits of heater materials). In some embodiments, the turndown ratio is increased by coupling additional copper or another good electrical conductor to the ferromagnetic material (for example, adding copper to lower the resistance above the Curie temperature).

The temperature limited heater may provide a minimum heat output (power output) below the Curie temperature of the heater. In certain embodiments, the minimum heat output is at least 400 W/m (Watts per meter), 600 W/m, 700 W/m, 800 W/m, or higher up to 2000 W/m. The temperature limited heater reduces the amount of heat output by a section of the heater when the temperature of the section of the heater approaches or is above the Curie temperature. The reduced amount of heat may be substantially less than the heat output below the Curie temperature. In some embodiments, the reduced amount of heat is at most 400 W/m, 200 W/m, 100 W/m or may approach 0 W/m.

In some embodiments, AC frequency is adjusted to change the skin depth of the ferromagnetic material. For example, the skin depth of 1% carbon steel at room temperature is 0.132 cm at 60 Hz, 0.0762 cm at 180 Hz, and 0.046 cm at 440 Hz. Since heater diameter is typically larger than twice the skin depth, using a higher frequency (and thus a heater with a smaller diameter) reduces heater costs. For a fixed geometry, the higher frequency results in a higher turndown ratio. The turndown ratio at a higher frequency is calculated by multiplying the turndown ratio at a lower frequency by the square root of the higher frequency divided by the lower frequency. In some embodiments, a frequency between 100 Hz and 1000 Hz, between 140 Hz and 200 Hz, or between 400 Hz and 600 Hz is used (for example, 180 Hz, 540 Hz, or 720 Hz). In some embodiments, high frequencies may be used. The frequencies may be greater than 1000 Hz.

In certain embodiments, modulated DC (for example, chopped DC, waveform modulated DC, or cycled DC) may be used for providing electrical power to the temperature limited heater. A DC modulator or DC chopper may be coupled to a DC power supply to provide an output of modulated direct current. In some embodiments, the DC power supply may include means for modulating DC. One example of a DC modulator is a DC-to-DC converter system. DC-to-DC converter systems are generally known in the art. DC is typically modulated or chopped into a desired waveform. Waveforms for DC modulation include, but are not limited to, square-wave, sinusoidal, deformed sinusoidal, deformed square-wave, triangular, and other regular or irregular waveforms.

The modulated DC waveform generally defines the frequency of the modulated DC. Thus, the modulated DC waveform may be selected to provide a desired modulated DC frequency. The shape and/or the rate of modulation (such as the rate of chopping) of the modulated DC waveform may be varied to vary the modulated DC frequency. DC may be modulated at frequencies that are higher than generally available AC frequencies. For example, modulated DC may be provided at frequencies of at least 1000 Hz. Increasing the frequency of supplied current to higher values advantageously increases the turndown ratio of the temperature limited heater.

In certain embodiments, the modulated DC waveform is adjusted or altered to vary the modulated DC frequency. The DC modulator may be able to adjust or alter the modulated DC waveform at any time during use of the temperature limited heater and at high currents or voltages. Thus, modulated DC provided to the temperature limited heater is not limited to a single frequency or even a small set of frequency values. Waveform selection using the DC modulator typically allows for a wide range of modulated DC frequencies and for discrete control of the modulated DC frequency. Thus, the modulated DC frequency is more easily set at a distinct value whereas AC frequency is generally limited to multiples of the line frequency. Discrete control of the modulated DC frequency allows for more selective control over the turndown ratio of the temperature limited heater. Being able to selectively control the turndown ratio of the temperature limited heater allows for a broader range of materials to be used in designing and constructing the temperature limited heater.

In some embodiments, the modulated DC frequency or the AC frequency is adjusted to compensate for changes in properties (for example, subsurface conditions such as temperature or pressure) of the temperature limited heater during use. The modulated DC frequency or the AC frequency provided to the temperature limited heater is varied based on assessed downhole conditions. For example, as the temperature of the temperature limited heater in the wellbore increases, it may be advantageous to increase the frequency of the current provided to the heater, thus increasing the turndown ratio of the heater. In an embodiment, the downhole temperature of the temperature limited heater in the wellbore is assessed.

In certain embodiments, the modulated DC frequency, or the AC frequency, is varied to adjust the turndown ratio of the temperature limited heater. The turndown ratio may be adjusted to compensate for hot spots occurring along a length of the temperature limited heater. For example, the turndown ratio is increased because the temperature limited heater is getting too hot in certain locations. In some embodiments, the modulated DC frequency, or the AC frequency, are varied to adjust a turndown ratio without assessing a subsurface condition.

In certain embodiments, an outermost layer of the temperature limited heater (for example, the outer conductor) is chosen for corrosion resistance, yield strength, and/or creep resistance. In one embodiment, austenitic (non-ferromagnetic) stainless steels such as 201, 304H, 347H, 347HH, 316H, 310H, 347HP, NF709 (Nippon Steel Corp., Japan) stainless steels, or combinations thereof may be used in the outer conductor. The outermost layer may also include a clad conductor. For example, a corrosion resistant alloy such as 800H or 347H stainless steel may be clad for corrosion protection over a ferromagnetic carbon steel tubular. If high temperature strength is not required, the outermost layer may be constructed from ferromagnetic metal with good corrosion resistance such as one of the ferritic stainless steels. In one embodiment, a ferritic alloy of 82.3% by weight iron with 17.7% by weight chromium (Curie temperature of 678 °C) provides desired corrosion resistance.

The Metals Handbook, vol. 8, page 291 (American Society of Materials (ASM)) includes a graph of Curie temperature of iron-chromium alloys versus the amount of chromium in the alloys. In some temperature limited heater embodiments, a separate support rod or tubular (made from 347H stainless steel) is coupled to the temperature limited heater made from an iron-chromium alloy to provide yield strength and/or creep resistance. In certain embodiments, the support material and/or the ferromagnetic material is selected to provide a 100,000 hour creep-rupture strength of at least 20.7 MPa at 650 °C. In some embodiments, the 100,000 hour creep-rupture strength is at least 13.8 MPa at 650 °C or at least 6.9 MPa at 650 °C. For example, 347H steel has a favorable creep-rupture strength at or above 650°C. In some embodiments, the 100,000 hour creep-rupture strength ranges from 6.9 MPa to 41.3 MPa or more for longer heaters and/or higher earth or fluid stresses.

In certain embodiments, the temperature limited heater includes a composite conductor with a ferromagnetic tubular and a non-ferromagnetic, high electrical conductivity core. The non-ferromagnetic, high electrical conductivity core reduces a required diameter of the conductor. For example, the conductor may be composite 1.19 cm diameter conductor with a core of 0.575 cm diameter copper clad with a 0.298 cm thickness of ferritic stainless steel or carbon steel surrounding the core. The core or non-ferromagnetic conductor may be copper or copper alloy. The core or non-ferromagnetic conductor may also be made of other metals that exhibit low electrical resistivity and relative magnetic permeabilities near 1 (for example, substantially non-ferromagnetic materials such as aluminum and aluminum alloys, phosphor bronze, beryllium copper, and/or brass). A composite conductor allows the electrical resistance of the temperature limited heater to decrease more steeply near the Curie temperature. As the skin depth increases near the Curie temperature to include the copper core, the electrical resistance decreases very sharply.

The composite conductor may increase the conductivity of the temperature limited heater and/or allow the heater to operate at lower voltages. In an embodiment, the composite conductor exhibits a relatively flat resistance versus temperature profile at temperatures below a region near the Curie temperature of the ferromagnetic conductor of the composite conductor. In some embodiments, the temperature limited heater exhibits a relatively flat resistance versus temperature profile between 100 °C and 750 °C or between 300 °C and 600 °C. The relatively flat resistance versus temperature profile may also be exhibited in other temperature ranges by adjusting, for example, materials and/or the configuration of materials in the temperature limited heater. In certain embodiments, the relative thickness of each material in the composite conductor is selected to produce a desired resistivity versus temperature profile for the temperature limited heater.

A composite conductor (for example, a composite inner conductor or a composite outer conductor) may be manufactured by methods including, but not limited to, coextrusion, roll forming, tight fit tubing (for example, cooling the inner member and heating the outer member, then inserting the inner member in the outer member, followed by a drawing operation and/or allowing the system to cool), explosive or electromagnetic cladding, arc overlay welding, longitudinal strip welding, plasma powder welding, billet coextrusion, electroplating, drawing, sputtering, plasma deposition, coextrusion casting, magnetic forming, molten cylinder casting (of inner core material inside the outer or vice versa), insertion followed by welding or high temperature braising, shielded active gas welding (SAG), and/or insertion of an inner pipe in an outer pipe followed by mechanical expansion of the inner pipe by hydroforming or use of a pig to expand and swage the inner pipe against the outer pipe. In some embodiments, a ferromagnetic conductor is braided over a non-ferromagnetic conductor. In certain embodiments, composite conductors are formed using methods similar to those used for cladding (for example, cladding copper to steel). A metallurgical bond between copper cladding and base ferromagnetic material may be advantageous. Composite conductors produced by a coextrusion process that forms a good metallurgical bond (for example, a good bond between copper and 446 stainless steel) may be provided by Anomet Products, Inc. (Shrewsbury, Massachusetts, U.S.A.).

FIGS. 3-9 depict various embodiments of temperature limited heaters. One or more features of an embodiment of the temperature limited heater depicted in any of these figures may be combined with one or more features of other embodiments of temperature limited heaters depicted in these figures. In certain embodiments described herein, temperature limited heaters are dimensioned to operate at a frequency of 60 Hz AC. It is to be understood that dimensions of the temperature limited heater may be adjusted from those described herein in order for the temperature limited heater to operate in a similar manner at other AC frequencies or with modulated DC current.

FIG. 3 depicts a cross-sectional representation of an embodiment of the temperature limited heater with an outer conductor having a ferromagnetic section and a non-ferromagnetic section. FIGS. 4 and 5 depict transverse cross-sectional views of the embodiment shown in FIG. 3. In one embodiment, ferromagnetic section 212 is used to provide heat to hydrocarbon layers in the formation. Non-ferromagnetic section 214 is used in the overburden of the formation. Non-ferromagnetic section 214 provides little or no heat to the overburden, thus inhibiting heat losses in the overburden and improving heater efficiency. Ferromagnetic section 212 includes a ferromagnetic material such as 409 stainless steel or 410 stainless steel. Ferromagnetic section 212 has a thickness of 0.3 cm. Non-ferromagnetic section 214 is copper with a thickness of 0.3 cm. Inner conductor 216 is copper. Inner conductor 216 has a diameter of 0.9 cm. Electrical insulator 218 is silicon nitride, boron nitride, magnesium oxide powder, or another suitable insulator material. Electrical insulator 218 has a thickness of 0.1 cm to 0.3 cm.

FIG. 6A and FIG. 6B depict cross-sectional representations of an embodiment of a temperature limited heater with a ferromagnetic inner conductor and a non-ferromagnetic core. Inner conductor 216 may be made of 446 stainless steel, 409 stainless steel, 410 stainless steel, carbon steel, Armco ingot iron, iron-cobalt alloys, or other ferromagnetic materials. Core 220 may be tightly bonded inside inner conductor 216. Core 220 is copper or other non-ferromagnetic material. In certain embodiments, core 220 is inserted as a tight fit inside inner conductor 216 before a drawing operation. In some embodiments, core 220 and inner conductor 216 are coextrusion bonded. Outer conductor 222 is 347H stainless steel. A drawing or rolling operation to compact electrical insulator 218 (for example, compacted silicon nitride, boron nitride, or magnesium oxide powder) may ensure good electrical contact between inner conductor 216 and core 220. In this embodiment, heat is produced primarily in inner conductor 216 until the Curie temperature is approached. Resistance then decreases sharply as current penetrates core 220.

For a temperature limited heater in which the ferromagnetic conductor provides a majority of the resistive heat output below the Curie temperature, a majority of the current flows through material with highly non-linear functions of magnetic field (H) versus magnetic induction (B). These non-linear functions may cause strong inductive effects and distortion that lead to decreased power factor in the temperature limited heater at temperatures below the Curie temperature. These effects may render the electrical power supply to the temperature limited heater difficult to control and may result in additional current flow through surface and/or overburden power supply conductors. Expensive and/or difficult to implement control systems such as variable capacitors or modulated power supplies may be used to attempt to compensate for these effects and to control temperature limited heaters where the majority of the resistive heat output is provided by current flow through the ferromagnetic material.

In certain temperature limited heater embodiments, the ferromagnetic conductor confines a majority of the flow of electrical current to an electrical conductor coupled to the ferromagnetic conductor when the temperature limited heater is below or near the Curie temperature of the ferromagnetic conductor. The electrical conductor may be a sheath, jacket, support member, corrosion resistant member, or other electrically resistive member. In some embodiments, the ferromagnetic conductor confines a majority of the flow of electrical current to the electrical conductor positioned between an outermost layer and the ferromagnetic conductor. The ferromagnetic conductor is located in the cross section of the temperature limited heater such that the magnetic properties of the ferromagnetic conductor at or below the Curie temperature of the ferromagnetic conductor confine the majority of the flow of electrical current to the electrical conductor. The majority of the flow of electrical current is confined to the electrical conductor due to the skin effect of the ferromagnetic conductor. Thus, the majority of the current is flowing through material with substantially linear resistive properties throughout most of the operating range of the heater.

In certain embodiments, the ferromagnetic conductor and the electrical conductor are located in the cross section of the temperature limited heater so that the skin effect of the ferromagnetic material limits the penetration depth of electrical current in the electrical conductor and the ferromagnetic conductor at temperatures below the Curie temperature of the ferromagnetic conductor. Thus, the electrical conductor provides a majority of the electrically resistive heat output of the temperature limited heater at temperatures up to a temperature at or near the Curie temperature of the ferromagnetic conductor. In certain embodiments, the dimensions of the electrical conductor may be chosen to provide desired heat output characteristics.

Because the majority of the current flows through the electrical conductor below the Curie temperature, the temperature limited heater has a resistance versus temperature profile that at least partially reflects the resistance versus temperature profile of the material in the electrical conductor. Thus, the resistance versus temperature profile of the temperature limited heater is substantially linear below the Curie temperature of the ferromagnetic conductor if the material in the electrical conductor has a substantially linear resistance versus temperature profile. The resistance of the temperature limited heater has little or no dependence on the current flowing through the heater until the temperature nears the Curie temperature. The majority of the current flows in the electrical conductor rather than the ferromagnetic conductor below the Curie temperature.

Resistance versus temperature profiles for temperature limited heaters in which the majority of the current flows in the electrical conductor also tend to exhibit sharper reductions in resistance near or at the Curie temperature of the ferromagnetic conductor. The sharper reductions in resistance near or at the Curie temperature are easier to control than more gradual resistance reductions near the Curie temperature.

In certain embodiments, the material and/or the dimensions of the material in the electrical conductor are selected so that the temperature limited heater has a desired resistance versus temperature profile below the Curie temperature of the ferromagnetic conductor.

Temperature limited heaters in which the majority of the current flows in the electrical conductor rather than the ferromagnetic conductor below the Curie temperature are easier to predict and/or control. Behavior of temperature limited heaters in which the majority of the current flows in the electrical conductor rather than the ferromagnetic conductor below the Curie temperature may be predicted by, for example, its resistance versus temperature profile and/or its power factor versus temperature profile. Resistance versus temperature profiles and/or power factor versus temperature profiles may be assessed or predicted by, for example, experimental measurements that assess the behavior of the temperature limited heater, analytical equations that assess or predict the behavior of the temperature limited heater, and/or simulations that assess or predict the behavior of the temperature limited heater.

As the temperature of the temperature limited heater approaches or exceeds the Curie temperature of the ferromagnetic conductor, reduction in the ferromagnetic properties of the ferromagnetic conductor allows electrical current to flow through a greater portion of the electrically conducting cross section of the temperature limited heater. Thus, the electrical resistance of the temperature limited heater is reduced and the temperature limited heater automatically provides reduced heat output at or near the Curie temperature of the ferromagnetic conductor. In certain embodiments, a highly electrically conductive member is coupled to the ferromagnetic conductor and the electrical conductor to reduce the electrical resistance of the temperature limited heater at or above the Curie temperature of the ferromagnetic conductor. The highly electrically conductive member may be an inner conductor, a core, or another conductive member of copper, aluminum, nickel, or alloys thereof.

The ferromagnetic conductor that confines the majority of the flow of electrical current to the electrical conductor at temperatures below the Curie temperature may have a relatively small cross section compared to the ferromagnetic conductor in temperature limited heaters that use the ferromagnetic conductor to provide the majority of resistive heat output up to or near the Curie temperature. A temperature limited heater that uses the electrical conductor to provide a majority of the resistive heat output below the Curie temperature has low magnetic inductance at temperatures below the Curie temperature because less current is flowing through the ferromagnetic conductor as compared to the temperature limited heater where the majority of the resistive heat output below the Curie temperature is provided by the ferromagnetic material. Magnetic field (H) at radius (r) of the ferromagnetic conductor is proportional to the current (I) flowing through the ferromagnetic conductor and the core divided by the radius, or:

(2) $H \propto I/r$.

Since only a portion of the current flows through the ferromagnetic conductor for a temperature limited heater that uses the outer conductor to provide a majority of the resistive heat output below the Curie temperature, the magnetic field of the temperature limited heater may be significantly smaller than the magnetic field of the temperature limited heater where the majority of the current flows through the ferromagnetic material. The relative magnetic permeability (μ) may be large for small magnetic fields.

The skin depth (δ) of the ferromagnetic conductor is inversely proportional to the square root of the relative magnetic permeability (μ):

(3) $\delta \propto (1/\mu)^{1/2}$.

Increasing the relative magnetic permeability decreases the skin depth of the ferromagnetic conductor. However, because only a portion of the current flows through the ferromagnetic conductor for temperatures below the Curie temperature, the radius (or thickness) of the ferromagnetic conductor may be decreased for ferromagnetic materials with large relative magnetic permeabilities to compensate for the decreased skin depth while still allowing the skin effect to limit the penetration depth of the electrical current to the electrical conductor at temperatures below the Curie temperature of the ferromagnetic conductor. The radius (thickness) of the ferromagnetic conductor may be between 0.3 mm and 8 mm, between 0.3 mm and 2 mm, or between 2 mm and 4 mm depending on the relative magnetic permeability of the ferromagnetic conductor. Decreasing the thickness of the ferromagnetic conductor decreases costs of manufacturing the temperature limited heater, as the cost of ferromagnetic material tends to be a significant portion of the cost of the temperature limited heater. Increasing the relative magnetic permeability of the ferromagnetic conductor provides a higher turndown ratio and a sharper decrease in electrical resistance for the temperature limited heater at or near the Curie temperature of the ferromagnetic conductor.

Ferromagnetic materials (such as purified iron or iron-cobalt alloys) with high relative magnetic permeabilities (for example, at least 200, at least 1000, at least 1×10^4, or at least 1×10^5) and/or high Curie temperatures (for example, at least 600 °C, at least 700 °C, or at least 800 °C) tend to have less corrosion resistance and/or less mechanical strength at high temperatures. The electrical conductor may provide corrosion resistance and/or high mechanical strength at high temperatures for the temperature limited heater. Thus, the ferromagnetic conductor may be chosen primarily for its ferromagnetic properties.

Confining the majority of the flow of electrical current to the electrical conductor below the Curie temperature of the ferromagnetic conductor reduces variations in the power factor. Because only a portion of the electrical current flows through the ferromagnetic conductor below the Curie temperature, the non-linear ferromagnetic properties of the ferromagnetic conductor have little or no effect on the power factor of the temperature limited heater, except at or near the Curie temperature. Even at or near the Curie temperature, the effect on the power factor is reduced compared to temperature limited heaters in which the ferromagnetic conductor provides a majority of the resistive heat output below the Curie temperature. Thus, there is less or no need for external compensation (for example, variable capacitors or waveform modification) to adjust for changes in the inductive load of the temperature limited heater to maintain a relatively high power factor.

In certain embodiments, the temperature limited heater, which confines the majority of the flow of electrical current to the electrical conductor below the Curie temperature of the ferromagnetic conductor, maintains the power factor above 0.85, above 0.9, or above 0.95 during use of the heater. Any reduction in the power factor occurs only in sections of the temperature limited heater at temperatures near the Curie temperature. Most sections of the temperature limited heater are typically not at or near the Curie temperature during use. These sections have a high power factor that approaches 1.0. The power factor for the entire temperature limited heater is maintained above 0.85, above 0.9, or above 0.95 during use of the heater even if some sections of the heater have power factors below 0.85.

Maintaining high power factors also allows for less expensive power supplies and/or control devices such as solid state power supplies or SCRs (silicon controlled rectifiers). These devices may fail to operate properly if the power factor varies by too large an amount because of inductive loads. With the power factors maintained at the higher values; however, these devices may be used to provide power to the temperature limited heater. Solid state power supplies also have the advantage of allowing fine tuning and controlled adjustment of the power supplied to the temperature limited heater.

In some embodiments, transformers are used to provide power to the temperature limited heater. Multiple voltage taps may be made into the transformer to provide power to the temperature limited heater. Multiple voltage taps allows the current supplied to switch back and forth between the multiple voltages. This maintains the current within a range bound by the multiple voltage taps.

The highly electrically conductive member, or inner conductor, increases the turndown ratio of the temperature limited heater. In certain embodiments, thickness of the highly electrically conductive member is increased to increase the turndown ratio of the temperature limited heater. In some embodiments, the thickness of the electrical conductor is reduced to increase the turndown ratio of the temperature limited heater. In certain embodiments, the turndown ratio of the temperature limited heater is between 1.1 and 10, between 2 and 8, or between 3 and 6 (for example, the turndown ratio is at least 1.1, at least 2, or at least 3).

FIG. 7 depicts an embodiment of a temperature limited heater in which the support member provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor. Core 220 is an inner conductor of the temperature limited heater. In certain embodiments, core 220 is a highly electrically conductive material such as copper or aluminum. In some embodiments, core 220 is a copper alloy that provides mechanical strength and good electrically conductivity such as a dispersion strengthened copper. In one embodiment, core 220 is Glidcop® (SCM Metal Products, Inc., Research Triangle Park, North Carolina, U.S.A.). Ferromagnetic conductor 224 is a thin layer of ferromagnetic material between electrical conductor 226 and core 220. In certain embodiments, electrical conductor 226 is also support member 228. In certain embodiments, ferromagnetic conductor 224 is iron or an iron alloy. In some embodiments, ferromagnetic conductor 224 includes ferromagnetic material with a high relative magnetic permeability. For example, ferromagnetic conductor 224 may be purified iron such as Armco ingot iron (AK Steel Ltd., United Kingdom). Iron with some impurities typically has a relative magnetic permeability on the order of 400. Purifying the iron by annealing the iron in hydrogen gas (H_2) at 1450 °C increases the relative magnetic permeability of the iron. Increasing the relative magnetic permeability of ferromagnetic conductor 224 allows the thickness of the ferromagnetic conductor to be reduced. For example, the thickness of unpurified iron may be approximately 4.5 mm while the thickness of the purified iron is approximately 0.76 mm.

In certain embodiments, electrical conductor 226 provides support for ferromagnetic conductor 224 and the temperature limited heater. Electrical conductor 226 may be made of a material that provides good mechanical strength at temperatures near or above the Curie temperature of ferromagnetic conductor 224. In certain embodiments, electrical conductor 226 is a corrosion resistant member. Electrical conductor 226 (support member 228) may provide support for ferromagnetic conductor 224 and corrosion resistance. Electrical conductor 226 is made from a material that provides desired electrically resistive heat output at temperatures up to and/or above the Curie temperature of ferromagnetic conductor 224.

In an embodiment, electrical conductor 226 is 347H stainless steel. In some embodiments, electrical conductor 226 is another electrically conductive, good mechanical strength, corrosion resistant material. For example, electrical conductor 226 may be 304H, 316H, 347HH, NF709, Incoloy® 800H alloy (Inco Alloys International, Huntington, West Virginia, U.S.A.), Haynes® HR120® alloy, or Inconel® 617 alloy.

In some embodiments, electrical conductor 226 (support member 228) includes different alloys in different portions of the temperature limited heater. For example, a lower portion of electrical conductor 226 (support member 228) is 347H stainless steel and an upper portion of the electrical conductor (support member) is NF709. In certain embodiments, different alloys are used in different portions of the electrical conductor (support member) to increase the mechanical strength of the electrical conductor (support member) while maintaining desired heating properties for the temperature limited heater.

In some embodiments, ferromagnetic conductor 224 includes different ferromagnetic conductors in different portions of the temperature limited heater. Different ferromagnetic conductors may be used in different portions of the temperature limited heater to vary the Curie temperature and, thus, the maximum operating temperature in the different portions. In some embodiments, the Curie temperature in an upper portion of the temperature limited heater is lower than the Curie temperature in a lower portion of the heater. The lower Curie temperature in the upper portion increases the creep-rupture strength lifetime in the upper portion of the heater.

In the embodiment depicted in FIG. 7, ferromagnetic conductor 224, electrical conductor 226, and core 220 are dimensioned so that the skin depth of the ferromagnetic conductor limits the penetration depth of the majority of the flow of electrical current to the support member when the temperature is below the Curie temperature of the ferromagnetic conductor. Thus, electrical conductor 226 provides a majority of the electrically resistive heat output of the temperature limited heater at temperatures up to a temperature at or near the Curie temperature of ferromagnetic conductor 224. In certain embodiments, the temperature limited heater depicted in FIG. 7 is smaller (for example, an outside diameter of 3 cm, 2.9 cm, 2.5 cm, or less) than other temperature limited heaters that do not use electrical conductor 226 to provide the majority of electrically resistive heat output. The temperature limited heater depicted in FIG. 7 may be smaller because ferromagnetic conductor 224 is thin as compared to the size of the ferromagnetic conductor needed for a temperature limited heater in which the majority of the resistive heat output is provided by the ferromagnetic conductor.

In some embodiments, the support member and the corrosion resistant member are different members in the temperature limited heater. FIGS. 8 and 9 depict embodiments of temperature limited heaters in which the jacket provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor. In these embodiments, electrical conductor 226 is jacket 230. Electrical conductor 226, ferromagnetic conductor 224, support member 228, and core 220 (in FIG. 8) or inner conductor 216 (in FIG. 9) are dimensioned so that the skin depth of the ferromagnetic conductor limits the penetration depth of the majority of the flow of electrical current to the thickness of the jacket. In certain embodiments, electrical conductor 226 is a material that is corrosion resistant and provides electrically resistive heat output below the Curie temperature of ferromagnetic conductor 224. For example, electrical conductor 226 is 825 stainless steel or 347H stainless steel. In some embodiments, electrical conductor 226 has a small thickness (for example, on the order of 0.5 mm).

In FIG. 8, core 220 is highly electrically conductive material such as copper or aluminum. Support member 228 is 347H stainless steel or another material with good mechanical strength at or near the Curie temperature of ferromagnetic conductor 224.

In FIG. 9, support member 228 is the core of the temperature limited heater and is 347H stainless steel or another material with good mechanical strength at or near the Curie temperature of ferromagnetic conductor 224. Inner conductor 216 is highly electrically conductive material such as copper or aluminum.

The temperature limited heater may be a single-phase heater or a three-phase heater. In a three-phase heater embodiment, the temperature limited heater has a delta or a wye configuration. In some embodiments, the three-phase heater includes three legs that are located in separate wellbores. The legs may be coupled in a common contacting section (for example, a central wellbore, a connecting wellbore, or a solution filled contacting section). FIG. 10 depicts an embodiment of temperature limited heaters coupled together in a three-phase configuration. Each leg 232, 234, 236 may be located in separate openings 238 in hydrocarbon layer 240 below overburden 242. Each leg 232, 234, 236 may include heating element 244. Each leg 232, 234, 236 may be coupled to single contacting element 246 in one opening 238. Contacting element 246 may electrically couple legs 232, 234, 236 together in a three-phase configuration. Contacting element 246 may be located in, for example, a central opening in the formation. Contacting element 246 may be located in a portion of opening 238 below hydrocarbon layer 240 (for example, in the underburden). In certain embodiments, magnetic tracking of a magnetic element located in a central opening (for example, opening 238 with leg 234) is used to guide the formation of the outer openings (for example, openings 238 with legs 232 and 236) so that the outer openings intersect the central opening. The central opening may be formed first using standard wellbore drilling methods. Contacting element 246 may include funnels, guides, or catchers for allowing each leg to be inserted into the contacting element.

In certain embodiments, two legs in separate wellbores intercept in a single contacting section. FIG. 11 depicts an embodiment of two temperature limited heaters coupled together in a single contacting section. Legs 232 and 234 include one or more heating elements 244. Heating elements 244 may include one or more electrical conductors. In certain embodiments, legs 232 and 234 are electrically coupled in a single-phase configuration with one leg positively biased versus the other leg so that current flows downhole through one leg and returns through the other leg.

Heating elements 244 in legs 232 and 234 may be temperature limited heaters. In certain embodiments, heating elements 244 are solid rod heaters. For example, heating elements 244 may be rods made of a single ferromagnetic conductor element or composite conductors that include ferromagnetic material. During initial heating when water is present in the formation being heated, heating elements 244 may leak current into hydrocarbon layer 240. The current leaked into hydrocarbon layer 240 may resistively heat the hydrocarbon layer.

In some embodiments (for example, in oil shale formations), heating elements 244 do not need support members. Heating elements 244 may be partially or slightly bent, curved, made into an S-shape, or made into a helical shape to allow for expansion and/or contraction of the heating elements. In certain embodiments, solid rod heating elements 244 are placed in small diameter wellbores (for example, about 3 ¾" (about 9.5 cm) diameter wellbores). Small diameter wellbores may be less expensive to drill or form than larger diameter wellbores and have less cutting to dispose of.

In certain embodiments, portions of legs 232 and 234 in overburden 242 have insulation (for example, polymer insulation) to inhibit heating the overburden. Heating elements 244 may be substantially vertical and substantially parallel to each other in hydrocarbon layer 240. At or near the bottom of hydrocarbon layer 240, leg 232 may be directionally drilled towards leg 234 to intercept leg 234 in contacting section 248. Directional drilling may be done by, for example, Vector Magnetics LLC (Ithaca, New York, U.S.A.). The depth of contacting section 248 depends on the length of bend in leg 232 needed to intercept leg 234. For example, for a 40 ft (about 12 m) spacing between vertical portions of legs 232 and 234, about 200 ft (about 61 m) is needed to allow the bend of leg 232 to intercept leg 234.

FIG. 12 depicts an embodiment for coupling legs 232 and 234 in contacting section 248. Heating elements 244 are coupled to contacting elements 246 at or near junction of contacting section 248 and hydrocarbon layer 240. Contacting elements 246 may be copper or another suitable electrical conductor. In certain embodiments, contacting element 246 in leg 234 is a liner with opening 250. Contacting element 246 from leg 232 passes through opening 250. Contactor 252 is coupled to the end of contacting element 246 from leg 232. Contactor 252 provides electrical coupling between contacting elements in legs 232 and 234.

FIG. 13 depicts an embodiment for coupling legs 232 and 234 in contacting section 248 with contact solution 254 in the contacting section. Contact solution 254 is placed in portions of leg 232 and/or portions of leg 234 with contacting elements 246. Contact solution 254 promotes electrical contact between contacting elements 246. Contact solution 254 may be graphite based cement or another high electrical conductivity cement or solution (for example, brine or other ionic solutions).

In some embodiments, electrical contact is made between contacting elements 246 using only contact solution 254. FIG. 14 depicts an embodiment for coupling legs 232 and 234 in contacting section 248 without contactor 252. Contacting elements 246 may or may not touch in contacting section 248. Electrical contact between contacting elements 246 in contacting section 248 is made using contact solution 254.

In certain embodiments, contacting elements 246 include one or more fins or projections. The fins or projections may increase an electrical contact area of contacting elements 246. In some embodiments, legs 232 and 234 (for example, electrical conductors in heating elements 244) are electrically coupled together but do not physically contact each other. This type of electrical coupling may be accomplished with, for example, contact solution 254.

FIG. 15 depicts an embodiment of three heaters coupled in a three-phase configuration. Conductor "legs" 232, 234, 236 are coupled to three-phase transformer 256. Transformer 256 may be an isolated three-phase transformer. In certain embodiments, transformer 256 provides three-phase output in a wye configuration, as shown in FIG. 15. Input to transformer 256 may be made in any input configuration (such as the delta configuration shown in FIG. 15). Legs 232, 234, 236 each include lead-in conductors 258 in the overburden of the formation coupled to heating elements 244 in hydrocarbon layer 240. Lead-in conductors 258 include copper with an insulation layer. For example, lead-in conductors 258 may be a 4-0 copper cables with TEFLON® insulation, a copper rod with polyurethane insulation, or other metal conductors such as aluminum. Heating elements 244 may be temperature limited heater heating elements. In an embodiment, heating elements 244 are 410 stainless steel rods (for example, 3.1 cm diameter 410 stainless steel rods). In some embodiments, heating elements 244 are composite temperature limited heater heating elements (for example, 347 stainless steel, 410 stainless steel, copper composite heating elements; 347 stainless steel, iron, copper composite heating elements; or 410 stainless steel and copper composite heating elements). In certain embodiments, heating elements 244 have a length of at least about 10 m to about 2000 m, about 20 m to about 400 m, or about 30 m to about 300 m.

In certain embodiments, heating elements 244 are exposed to hydrocarbon layer 240 and fluids from the hydrocarbon layer. Thus, heating elements 244 are "bare metal" or "exposed metal" heating elements. Heating elements 244 may be made from a material that has an acceptable sulfidation rate at high temperatures used for pyrolyzing hydrocarbons. In certain embodiments, heating elements 244 are made from material that has a sulfidation rate that decreases with increasing temperature over at least a certain temperature range (for example, 530 °C to 650 °C), such as 410 stainless steel. Using such materials reduces corrosion problems due to sulfur-containing gases (such as H_2S) from the formation. Heating elements 244 may also be substantially inert to galvanic corrosion.

In some embodiments, heating elements 244 have a thin electrically insulating layer such as aluminum oxide or thermal spray coated aluminum oxide. In some embodiments, the thin electrically insulating layer is an enamel coating of a ceramic composition. These enamel coatings include, but are not limited to, high temperature porcelain enamels. High temperature porcelain enamels may include silicon dioxide, boron oxide, alumina, and alkaline earth oxides (CaO or MgO), and minor amounts of alkali oxides (Na_2O, K_2O, LiO). The enamel coating may be applied as a finely ground slurry by dipping the heating element into the slurry or spray coating the heating element with the slurry. The coated heating element is then heated in a furnace until the glass transition temperature is reached so that the slurry spreads over the surface of the heating element and makes the porcelain enamel coating. The porcelain enamel coating contracts when cooled below the glass transition temperature so that the coating is in compression. Thus, when the coating is heated during operation of the heater the coating is able to expand with the heater without cracking.

The thin electrically insulating layer has low thermal impedance allowing heat transfer from the heating element to the formation while inhibiting current leakage between heating elements in adjacent openings and current leakage into the formation. In certain embodiments, the thin electrically insulating layer is stable at temperatures above at least 350 °C, above 500 °C, or above 800 °C. In certain embodiments, the thin electrically insulating layer has an emissivity of at least 0.7, at least 0.8, or at least 0.9. Using the thin electrically insulating layer may allow for long heater lengths in the formation with low current leakage.

Heating elements 244 may be coupled to contacting elements 246 at or near the underburden of the formation. Contacting elements 246 are copper or aluminum rods or other highly conductive materials. In certain embodiments, transition sections 260 are located between lead-in conductors 258 and heating elements 244, and/or between heating elements 244 and contacting elements 246. Transition sections 260 may be made of a conductive material that is corrosion resistant such as 347 stainless steel over a copper core. In certain embodiments, transition sections 260 are made of materials that electrically couple lead-in conductors 258 and heating elements 244 while providing little or no heat output. Thus, transition sections 260 help to inhibit overheating of conductors and insulation used in lead-in conductors 258 by spacing the lead-in conductors from heating elements 244. Transition section 260 may have a length of between about 3 m and about 9 m (for example, about 6 m).

Contacting elements 246 are coupled to contactor 252 in contacting section 248 to electrically couple legs 232, 234, 236 to each other. In some embodiments, contact solution 254 (for example, conductive cement) is placed in contacting section 248 to electrically couple contacting elements 246 in the contacting section. In certain embodiments, legs 232, 234, 236 are substantially parallel in hydrocarbon layer 240 and leg 232 continues substantially vertically into contacting section 248. The other two legs 234, 236 are directed (for example, by directionally drilling the wellbores for the legs) to intercept leg 232 in contacting section 248.

Each leg 232, 234, 236 is one leg of a three-phase heater embodiment with the legs substantially electrically isolated from other heaters in the formation and substantially electrically isolated from the formation. Legs 232, 234, 236 may be arranged in a triangular pattern so that the three legs form a triad shaped three-phase heater that is substantially electrically isolated. In an embodiment, legs 232, 234, 236 are arranged in a triangular pattern with about 12 m spacing between the legs (each triad side has a length of about 12 m).

As shown in FIG. 15, contacting elements 246 of legs 232, 234, 236 may be coupled using contactor 252 and/or contact solution 254. In certain embodiments, contacting elements 246 of legs 232, 234, 236 are physically coupled, for example, through soldering, welding, or other techniques. FIGS. 16 and 17 depict an embodiments for coupling contacting elements 246 of legs 232, 234, 236. Legs 234, 236 may enter the wellbore of leg 232 from any direction desired. In one embodiment, legs 234, 236 enter the wellbore of leg 232 from approximately the same side of the wellbore, as shown in FIG. 16. In an alternative embodiment, legs 234, 236 enter the wellbore of leg 232 from approximately opposite sides of the wellbore, as shown in FIG. 17.

Container 262 is coupled to contacting element 246 of leg 232. Container 262 may be soldered, welded, or otherwise electrically coupled to contacting element 246. Container 262 is a metal can or other container with at least one opening for receiving one or more contacting elements 246. In an embodiment, container 262 is a can that has an opening for receiving contacting elements 246 from legs 234, 236, as shown in FIG. 16. In certain embodiments, wellbores for legs 234, 236 are drilled parallel to the wellbore for leg 232 through the hydrocarbon layer that is to be heated and directionally drilled below the hydrocarbon layer to intercept wellbore for leg 232 at an angle between about 10° and about 20° from vertical. Wellbores may be directionally drilled using known techniques such as techniques used by Vector Magnetics, Inc.

In some embodiments, contacting elements 246 contact the bottom of container 262. Contacting elements 246 may contact the bottom of container 262 and/or each other to promote electrical connection between the contacting elements and/or the container. In certain embodiments, end portions of contacting elements 246 are annealed to a "dead soft" condition to facilitate entry into container 262. In some embodiments, rubber or other softening material is attached to end portions of contacting elements 246 to facilitate entry into container 262. In some embodiments, contacting elements 246 include reticulated sections, such as knuckle-joints or limited rotation knuckle-joints, to facilitate entry into container 262.

In certain embodiments, an electrical coupling material is placed in container 262. The electrical coupling material may line the walls of container 262 or fill up a portion of the container. In certain embodiments, the electrical coupling material lines an upper portion, such as the funnel-shaped portion shown in FIG. 18, of container 262. The electrical coupling material includes one or more materials that when activated (for example, heated, ignited, exploded, combined, mixed, and/or reacted) form a material that electrically couples one or more elements to each other. In an embodiment, the coupling material electrically couples contacting elements 246 in container

262. In some embodiments, the coupling material metallically bonds to contacting elements 246 so that the contacting elements are metallically bonded to each other. In some embodiments, container 262 is initially filled with a high viscosity water-based polymer fluid to inhibit drill cuttings or other materials from entering the container prior to using the coupling material to couple the contacting elements. The polymer fluid may be, but is not limited to, a cross-linked XC polymer (available from Baroid Industrial Drilling Products (Houston, Texas, U.S.A.), a frac gel, or a cross-linked polyacrylamide gel.

In certain embodiments, the electrical coupling material is a low-temperature solder that melts at relatively low temperature and when cooled forms an electrical connection to exposed metal surfaces. In certain embodiments, the electrical coupling material is a solder that melts at a temperature below the boiling point of water at the depth of container 262. In one embodiment, the electrical coupling material is a 58% by weight bismuth and 42% by weight tin eutectic alloy. Other examples of such solders include, but are not limited to, a 54% by weight bismuth, 16% by weight tin, 30% by weight indium alloy, and a 48% by weight tin, 52% by weight indium alloy. Such low-temperature solders will displace water upon melting so that the water moves to the top of container 262. Water at the top of container 262 may inhibit heat transfer into the container and thermally insulate the low-temperature solder so that the solder remains at cooler temperatures and does not melt during heating of the formation using the heating elements.

Container 262 may be heated to activate the electrical coupling material to facilitate the connection of contacting elements 246. In certain embodiments, container 262 is heated to melt the electrical coupling material in the container. The electrical coupling material flows when melted and surrounds contacting elements 246 in container 262. Any water within container 262 will float to the surface of the metal when the metal is melted. The electrical coupling material is allowed to cool and electrically connects contacting elements 246 to each other. In certain embodiments, contacting elements 246 of legs 234, 236, the inside walls of container 262, and/or the bottom of the container are initially pre-tinned with electrical coupling material.

End portions of contacting elements 246 of legs 232, 234, 236 may have shapes and/or features that enhance the electrical connection between the contacting elements and the coupling material. The shapes and/or features of contacting elements 246 may also enhance the physical strength of the connection between the contacting elements and the coupling material (for example, the shape and/or features of the contacting element may anchor the contacting element in the coupling material). Shapes and/or features for end portions of contacting elements 246 include, but are not limited to, grooves, notches, holes, threads, serrated edges, openings, and hollow end portions. In certain embodiments, the shapes and/or features of the end portions of contacting elements 246 are initially pre-tinned with electrical coupling material.

FIG. 18 depicts an embodiment of container 262 with an initiator for melting the coupling material. The initiator is an electrical resistance heating element or any other element for providing heat that activates or melts the coupling material in container 262. In certain embodiments, heating element 264 is a heating element located in the walls of container 262. In some embodiments, heating element 264 is located on the outside of container 262. Heating element 264 may be, for example, a nichrome wire, a mineral-insulated conductor, a polymer-insulated conductor, a cable, or a tape that is inside the walls of container 262 or on the outside of the container. In some embodiments, heating element 264 wraps around the inside walls of the container or around the outside of the container. Lead-in wire 266 may be coupled to a power source at the surface of the formation. Lead-out wire 268 may be coupled to the power source at the surface of the formation. Lead-in wire 266 and/or lead-out wire 268 may be coupled along the length of leg 232 for mechanical support. Lead-in wire 266 and/or lead-out wire 268 may be removed from the wellbore after melting the coupling material. Lead-in wire 266 and/or lead-out wire 268 may be reused in other wellbores.

In some embodiments, container 262 has a funnel-shape, as shown in FIG. 18, that facilitates the entry of contacting elements 246 into the container. In certain embodiments, container 262 is made of or includes copper for good electrical and thermal conductivity. A copper container 262 makes good electrical contact with contacting elements (such as contacting elements 246 shown in FIGS. 16 and 17) if the contacting elements touch the walls and/or bottom of the container.

FIG. 19 depicts an embodiment of container 262 with bulbs on contacting elements 246. Protrusions 270 may be coupled to a lower portion of contacting elements 246. Protrusions 272 may be coupled to the inner wall of container 262. Protrusions 270, 272 may be made of copper or another suitable electrically conductive material. Lower portion of contacting element 246 of leg 236 may have a bulbous shape, as shown in FIG. 19. In certain embodiments, contacting element 246 of leg 236 is inserted into container 262. Contacting element 246 of leg 234 is inserted after insertion of contacting element 246 of leg 236. Both legs may then be pulled upwards simultaneously. Protrusions 270 may lock contacting elements 246 into place against protrusions 272 in container 262. A friction fit is created between contacting elements 246 and protrusions 270, 272.

Lower portions of contacting elements 246 inside container 262 may include 410 stainless steel or any other heat generating electrical conductor. Portions of contacting elements 246 above the heat generating portions of the contacting elements include copper or another highly electrically conductive material. Centralizers 273 may be located on the portions of contacting elements 246 above the heat generating portions of the contacting elements. Centralizers 273 inhibit physical and electrical contact of portions of contacting elements 246 above the heat generating portions of the contacting elements against walls of container 262.

When contacting elements 246 are locked into place inside container 262 by protrusions 270, 272, at least some electrical current may be pass between the contacting elements through the protrusions. As electrical current is passed through the heat generating portions of contacting elements 246, heat is generated in container 262. The generated heat may melt coupling material 274 located inside container 262. Water in container 262 may boil. The boiling water may convect heat to upper portions of container 262 and aid in melting of coupling material 274. Walls of container 262 may be thermally insulated to reduce heat losses out of the container and allow the inside of the container to heat up faster. Coupling material 274 flows down into the lower portion of container 262 as the coupling material melts. Coupling material 274 fills the lower portion of container 262 until the heat generating portions of contacting elements 246 are below the fill line of the coupling material. Coupling material 274 then electrically couples the portions of contacting elements 246 above the heat generating portions of the contacting elements. The resistance of contacting elements 246 decreases at this point and heat is no longer generated in the contacting elements and the coupling materials is allowed to cool.

In certain embodiments, container 262 includes insulation layer 275 inside the housing of the container. Insulation layer 275 may include thermally insulating materials to inhibit heat losses from the canister. For example, insulation layer 275 may include magnesium oxide, silicon nitride, or other thermally insulating materials that withstand operating temperatures in container 262. In certain embodiments, container 262 includes liner 277 on an inside surface of the container. Liner 277 may increase electrical conductivity inside container 262. Liner 277 may include electrically conductive materials such as copper or aluminum.

FIG. 20 depicts an alternative embodiment for container 262. Coupling material in container 262 includes powder 276. Powder 276 is a chemical mixture that produces a molten metal product from a reaction of the chemical mixture. In an embodiment, powder 276 is thermite powder. Powder 276 lines the walls of container 262 and/or is placed in the container. Igniter 278 is placed in powder 276. Igniter 278 may be, for example, a magnesium ribbon that when activated ignites the reaction of powder 276. When powder 276 reacts, a molten metal produced by the reaction flows and surrounds contacting elements 246 placed in container 262. When the molten metal cools, the cooled metal electrically connects contacting elements 246. In some embodiments, powder 276 is used in combination with another coupling material, such as a low-temperature solder, to couple contacting elements 246. The heat of reaction of powder 276 may be used to melt the low temperature-solder.

In certain embodiments, an explosive element is placed in container 262, depicted in FIG. 16 or FIG. 20. The explosive element may be, for example, a shaped charge explosive or other controlled explosive element. The explosive element may be exploded to crimp contacting elements 246 and/or container 262 together so that the contacting elements and the container are electrically connected. In some embodiments, an explosive element is used in combination with an electrical coupling material such as low-temperature solder or thermite powder to electrically connect contacting elements 246.

FIG. 21 depicts an alternative embodiment for coupling contacting elements 246 of legs 232, 234, 236. Container 262A is coupled to contacting element 246 of leg 234. Container 262B is coupled to contacting element 246 of leg 236. Container 262B is sized and shaped to be placed inside container 262A. Container 262C is coupled to contacting element 246 of leg 232. Container 262C is sized and shaped to be placed inside container 262B. In some embodiments, contacting element 246 of leg 232 is placed in container 262B without a container attached to the contacting element. One or more of containers 262A, 262B, 262C may be filled with a coupling material that is activated to facilitate an electrical connection between contacting elements 246 as described above.

FIG. 22 depicts a side view representation of an embodiment for coupling contacting elements using temperature limited heating elements. Contacting elements 246 of legs 232, 234, 236 may have insulation 280 on portions of the contacting elements above container 262. Container 262 may be shaped and/or have guides at the top to guide the insertion of contacting elements 246 into the container. Coupling material 274 may be located inside container 262 at or near a top of the container. Coupling material 274 may be, for example, a solder material. In some embodiments, inside walls of container 262 are pre-coated with coupling material or another electrically conductive material such as copper or aluminum. Centralizers 273 may be coupled to contacting elements 246 to maintain a spacing of the contacting elements in container 262. Container 262 may be tapered at the bottom to push lower portions of contacting elements 246 together for at least some electrical contact between the lower portions of the contacting elements.

Heating elements 282 may be coupled to portions of contacting elements 246 inside container 262. Heating elements 282 may include ferromagnetic materials such as iron or stainless steel. In an embodiment, heating elements 282 are iron cylinders clad onto contacting elements 246. Heating elements 282 may be designed with dimensions and materials that will produce a desired amount of heat in container 262. In certain embodiments, walls of container 262 are thermally insulated with insulation layer 275, as shown in FIG. 22 to inhibit heat loss from the container. Heating elements 282 may be spaced so that contacting elements 246 have one or more portions of exposed material inside container 262. The exposed portions include exposed copper or another suitable highly electrically conductive material. The exposed portions allow for better electrical contact between contacting elements 246 and coupling material 274 after the coupling material has been melted, fills container 262, and is allowed to cool.

In certain embodiments, heating elements 282 operate as temperature limited heaters when a time-varying current is applied to the heating elements. For example, a 400 Hz, AC current may be applied to heating elements 282. Application of the time-varying current to contacting elements 246 causes heating elements 282 to generate heat and melt coupling material 274. Heating elements 282 may operate as temperature limited heating elements with a self-limiting temperature selected so that coupling material 274 is not overheated. As coupling material 274 fills container 262, the coupling material makes electrical contact between portions of exposed material on contacting elements 246 and electrical current begins to flow through the exposed material portions rather than heating elements 282. Thus, the electrical resistance between the contacting elements decreases. As this occurs, temperatures inside container 262 begin to decrease and coupling material 274 is allowed to cool to create an electrical contacting section between contacting elements 246. In certain embodiments, electrical power to contacting elements 246 and heating elements 282 is turned off when the electrical resistance in the system falls below a selected resistance. The selected resistance may indicate that the coupling material has sufficiently electrically connected the contacting elements. In some embodiments, electrical power is supplied to contacting elements 246 and heating elements 282 for a selected amount of time that is determined to provide enough heat to melt the mass of coupling material 274 provided in container 262.

FIG. 23 depicts a side view representation of an alternative embodiment for coupling contacting elements using temperature limited heating elements. Contacting element 246 of leg 232 may be coupled to container 262 by welding, brazing, or another suitable method. Lower portion of contacting element 246 of leg 236 may have a bulbous shape. Contacting element 246 of leg 236 is inserted into container 262. Contacting element 246 of leg 234 is inserted after insertion of contacting element 246 of leg 236. Both legs may then be pulled upwards simultaneously. Protrusions 272 may lock contacting elements 246 into place and a friction fit may be created between the contacting elements 246. Centralizers 273 may inhibit electrical contact between upper portions of contacting elements 246.

Time-varying electrical current may be applied to contacting elements 246 so that heating elements 282 generate heat. The generated heat may melt coupling material 274 located in container 262 and be allowed to cool, as described for the embodiment depicted in FIG. 22. After cooling of coupling material 274, contacting elements 246 of legs 234, 236, shown in FIG. 23, are electrically coupled in container 262 with the coupling material. In some embodiments, lower portions of contacting elements 246 have protrusions or openings that anchor the contacting elements in cooled coupling material. Exposed portions of the contacting elements provide a low electrical resistance path between the contacting elements and the coupling material.

FIG. 24 depicts a side view representation of another alternative embodiment for coupling contacting elements using temperature limited heating elements. Contacting element 246 of leg 232 may be coupled to container 262 by welding, brazing, or another suitable method. Lower portion of contacting element 246 of leg 236 may have a bulbous shape. Contacting element 246 of leg 236 is inserted into container 262. Contacting element 246 of leg 234 is inserted after insertion of contacting element 246 of leg 236. Both legs may then be pulled upwards simultaneously. Protrusions 272 may lock contacting elements 246 into place and a friction fit may be created between the contacting elements 246. Centralizers 273 may inhibit electrical contact between upper portions of contacting elements 246.

End portions 246B of contacting elements 246 may be made of a ferromagnetic material such as 410 stainless steel. Portions 246A may include non-ferromagnetic electrically conductive material such as copper or aluminum. Time-varying electrical current may be applied to contacting elements 246 so that end portions 246B generate heat due to the resistance of the end portions. The generated heat may melt coupling material 274 located in container 262 and be allowed to cool, as described for the embodiment depicted in FIG. 22. After cooling of coupling material 274, contacting elements 246 of legs 234, 236, shown in FIG. 23, are electrically coupled in container 262 with the coupling material. Portions 246A may be below the fill line of coupling material 274 so that these portions of the contacting elements provide a low electrical resistance path between the contacting elements and the coupling material.

FIG. 25 depicts a side view representation of an alternative embodiment for coupling contacting elements of three legs of a heater. FIG. 26 depicts a top-view representation of the alternative embodiment for coupling contacting elements of three legs of a heater depicted in FIG. 25. Container 262 may include inner container 284 and outer container 286. Inner container 284 may be made of copper or another malleable, electrically conductive metal such as aluminum. Outer container 286 may be made of a rigid material such as stainless steel. Outer container 286 protects inner container 284 and its contents from environmental conditions outside of container 262.

Inner container 284 may be substantially solid with two openings 288 and 290. Inner container 284 is coupled to contacting element 246 of leg 232. For example, inner container 284 may be welded or brazed to contacting element 246 of leg 232. Openings 288, 290 are shaped to allow contacting elements 246 of legs 234, 236 to enter the openings as shown in FIG. 25. Funnels or other guiding mechanisms may be coupled to the entrances to openings 288, 290 to guide contacting elements 246 of legs 234, 236 into the openings. Contacting elements 246 of legs 232, 234, 236 may be made of the same material as inner container 284.

Explosive elements 292 may be coupled to the outer wall of inner container 284. In certain embodiments, explosive elements 292 are elongated explosive strips that extend along the outer wall of inner container 284. Explosive elements 292 may be arranged along the outer wall of inner container 284 so that the explosive elements are aligned at or near the centers of contacting elements 246, as shown in FIG. 26. Explosive elements 292 are arranged in this configuration so that energy from the explosion of the explosive elements causes contacting elements 246 to be pushed towards the center of inner container 284.

Explosive elements 292 may be coupled to battery 294 and timer 296. Battery 294 may provide power to explosive elements 292 to initiate the explosion. Timer 296 may be used to control the time for igniting explosive elements 292. Battery 294 and timer 296 may be coupled to triggers 298. Triggers 298 may be located in openings 288, 290. Contacting elements 246 may set off triggers 298 as the contacting elements are placed into openings 288, 290. When both triggers 298 in openings 288, 290 are triggered, timer 296 may initiate a countdown before igniting explosive elements 292. Thus, explosive elements 292 are controlled to explode only after contacting elements 246 are placed sufficiently into openings 288, 290 so that electrical contact may be made between the contacting elements and inner container 284 after the explosions. Explosion of explosive elements 292 crimps contacting elements 246 and inner container 284 together to make electrical contact between the contacting elements and the inner container. In certain embodiments, explosive elements 292 fire from the bottom towards the top of inner container 284. Explosive elements 292 may be designed with a length and explosive power (band width) that gives an optimum electrical contact between contacting elements 246 and inner container 284.

In some embodiments, triggers 298, battery 294, and timer 296 may be used to ignite a powder (for example, copper thermite powder) inside a container (for example, container 262 or inner container 284). Battery 294 may charge a magnesium ribbon or other ignition device in the powder to initiate reaction of the powder to produce a molten metal product. The molten metal product may flow and then cool to electrically contact the contacting elements.

In certain embodiments, electrical connection is made between contacting elements 246 through mechanical means. FIG. 27 depicts an embodiment of contacting element 246 with a brush contactor. Brush contactor 300 is coupled to a lower portion of contacting element 246. Brush contactor 300 may be made of a malleable, electrically conductive material such as copper or aluminum. Brush contactor 300 may be a webbing of material that is compressible and/or flexible. Centralizer 273 may be located at or near the bottom of contacting element 246.

FIG. 28 depicts an embodiment for coupling contacting elements 246 with brush contactors 300. Brush contactors 300 are coupled to each contacting element 246 of legs 232, 234, 236. Brush contactors 300 compress against each other and interlace to electrically couple contacting elements 246 of legs 232, 234, 236. Centralizers 273 maintain spacing between contacting elements 246 of legs 232, 234, 236 so that interference and/or clearance issues between the contacting elements are inhibited.

In certain embodiments, contacting elements 246 (depicted in FIGS. 16-28) are coupled in a zone of the formation that is cooler than the layer of the formation to be heated (for example, in the underburden of the formation). Contacting elements 246 are coupled in a cooler zone to inhibit melting of the coupling material and/or degradation of the electrical connection between the elements during heating of the hydrocarbon layer above the cooler zone. In certain embodiments, contacting elements 246 are coupled in a zone that is at least about 3 m, at least about 6 m, or at least about 9 m below the layer of the formation to be heated. In some embodiments, the zone has a standing water level that is above a depth of containers 262.

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 without departing from the spirit and scope of the invention as described in the following claims. In addition, it is to be understood that features described herein independently may, in certain embodiments, be combined.

CLAIMS

1. A system for heating a subsurface formation, comprising:

a first elongated heater in a first opening in the formation, wherein the first elongated heater includes an exposed metal section in a portion of the first opening, the portion being below a layer of the formation to be heated, and the exposed metal section being exposed to the formation;

a second elongated heater in a second opening in the formation, wherein the second opening connects to the first opening at or near the portion of the first opening below the layer to be heated; and

wherein at least a portion of an exposed metal section of the second elongated heater is electrically coupled to at least a portion of the exposed metal section of the first elongated heater in the portion of the first opening below the layer to be heated.

2. The system of claim 1, wherein at least one of the elongated heaters is at least about 30 m in length.

3. The system of any one of claims 1-2, the system comprising in addition a third elongated heater in a third opening in the formation, the third opening connecting to the first opening at or near the portion of the first opening below the layer to be heated, the third elongated heater having at least a portion of an exposed metal section electrically coupled to at least a portion of the exposed metal section of the first elongated heater.

4. The system of any one of claims 1-3, wherein the exposed metal section of the first elongated heater is at least about 3 m below the layer of the formation to be heated.

5. The system of any one of claims 1-4, wherein the electrical coupling between the first elongated heater and the second elongated heater has been made below an initial standing water level in the first opening.

6. The system of any one of claims 1-5, wherein the exposed metal section of the first elongated heater is in a zone that is heated less than the layer to be heated.

7. The system of any one of claims 1-6, wherein at least one of the elongated heaters comprises a temperature limited heater, the temperature limited heater comprising a ferromagnetic conductor and being configured to provide, when a time varying current is applied to the temperature limited heater, and when the heater is below a selected temperature, an electrical resistance and, when the ferromagnetic conductor is at or above the selected temperature, the temperature limited heater automatically provides a reduced electrical resistance.

8. A system for coupling heaters in the system of any one of claims 1-7, the system for coupling comprising:

a container configured to be coupled to an end portion of at least one of the heaters, the end portion being below the layer to be heated, the container comprising an electrical coupling material configured to facilitate, when melted and then cooled, an electrical connection between the first elongated heater and the second elongated heater.

9. The system of claim 8, wherein the electrical coupling material has a melting point below the boiling point of water at a depth of the container.

10. The system of any one of claims 8-9, the system comprising in addition an initiator coupled to the container, the initiator configured to melt the electrical coupling material.

11. The system of claim 10, wherein the initiator includes a heating element that melts the electrical coupling material.

12. The system of any one of claims 8-11, wherein the electrical coupling material includes a chemical mixture that chemically reacts when initiated, and the chemical reaction of the mixture produces a metal.

13. The system of claim 12, the system comprising in addition an igniter to initiate the chemical mixture reaction.

14. The system of any one of claims 8-13, wherein the electrical coupling material comprises solder.

15. A system for coupling heaters in the system of any one of claims 1-14, the system for coupling comprising:

an explosive element configured to be coupled to an end portion of at least one of the heaters, wherein the end portion is below the layer to be heated, and the explosive element being configured to facilitate, when exploded, an electrical connection between the first elongated heater and the second elongated heater.

16. The system of claim 15, the system comprising in addition an initiator coupled to the explosive element, the initiator configured to initiate the explosion of the explosive element.

17. The system of any one of claims 15-16, the system comprising in addition a container coupled to the end portion of at least one of the elongated heaters, the container configured to contain the explosive element such that the container contains the explosion of the explosive element.

18. A system for coupling heaters in the system of any one of claims 1-17, the system for coupling comprising:

a container configured to be coupled to an end portion of at least one of the heaters, the end portion being below the layer to be heated, the container comprising one or more openings for at least one additional elongated heater to be inserted into the container; and

one or more explosive elements configured to be coupled to the container, the explosive elements being configured to facilitate, when exploded, an electrical connection between the first elongated heater and the additional elongated heater.

19. The system of claim 18, the system comprising in addition a battery, the battery configured to provide power to the explosive elements.

20. The system of any one of claims 18-19, the system comprising in addition one or more triggers in the openings, the triggers configured to trigger the explosion of the explosive elements after at least one additional elongated heater is placed in at least one opening.

21. The system of any one of claims 18-19, wherein the explosive elements are configured to crimp together the elongated heaters such that the elongated heaters are electrically coupled.

22. The system of any one of claims 8-21, wherein the container is a funnel-shaped container.

23. The system of any one of claims 8-22, wherein the end portion of at least one of the elongated heaters has one or more grooves and/or one or more openings configured to enhance electrical connection between the heaters and between the heaters and the electrical coupling material.

24. The system of any one of claims 1-23, wherein at least one elongated heater comprises an exposed metal elongated heater section having a sulfidation rate that decreases with increasing temperature of the heater, when the heater section is between 530 °C and 650 °C.

25. The system of claim 24, wherein the exposed metal elongated heater section comprises 410 stainless steel.

26. The system of any one of claims 24-25, wherein the exposed metal elongated heater section is substantially inert to galvanic corrosion.

27. The system of any one of claims 1-26, wherein at least the portion of the exposed metal section of the second elongated heater is metallically bonded to at least the portion of the exposed metal section of the first elongated heater.

28. A method for coupling heaters in the system of any one of claims 1-27, the method comprising:

placing the first elongated heater in the first opening in the formation;

placing the second elongated heater in the second opening in the formation; and

coupling the exposed metal section of the second elongated heater to the exposed metal section of the first elongated heater in the portion of the first opening below the layer to be heated such that the exposed metal section of the first elongated heater is electrically coupled to the exposed metal section of the second elongated heater.

29. The method of claim 28, further comprising coupling the exposed metal section of the second elongated heater to the exposed metal section of the first elongated heater by:

placing an end portion of the exposed metal section of the second elongated heater in a container coupled to an end portion of the exposed metal section of the first elongated heater;

melting a metal in the container; and

allowing the metal in the container to cool to create an electrical connection between the first elongated heater and the second elongated heater.

30. The method of claim 29, further comprising melting the electrical coupling material at a temperature below the boiling point of water at a depth of the container.

31. The method of any one of claims 29-30, further comprising displacing water in the container by melting the electrical coupling material.

32. The method of any one of claims 29-31, further comprising using an initiator to melt the electrical coupling material.

33. The method of any one of claims 29-32, further comprising using a heating element to melt the electrical coupling material.

34. The method of any one of claims 29-33, further comprising initiating a chemical reaction of a chemical mixture to produce the electrical coupling material.

35. The method of any one of claims 28-34, further comprising coupling the exposed metal section of the second elongated heater to the exposed metal section of the first elongated heater by:

coupling an explosive element to an end portion of the exposed metal section of the first elongated heater;

placing an end portion of the exposed metal section of the second elongated heater near the explosive element; and

exploding the explosive element to create an electrical connection between the first elongated heater and the second elongated heater.

36. The method of any one of claims 28-35, further comprising coupling the exposed metal section of the second elongated heater to the exposed metal section of the first elongated heater by:

placing an end portion of the exposed metal section of the second elongated heater in an opening in a container coupled to the exposed metal section of the first elongated heater; and

exploding one or more explosive elements coupled to the container to create an electrical connection between the first elongated heater and the second elongated heater.

37. The method of any one of claims 28-36, wherein the exposed metal section of the first elongated heater is electrically coupled to the exposed metal section of the second elongated heater below a water level in the formation.

38. The method of any one of claims 28-37, wherein the exposed metal section of the first elongated heater is metallically bonded to the exposed metal section of the second elongated heater below a water level in the formation.

39. A method using the system as claimed in any of claims 1-27, the method comprising providing heat to at least a portion of the formation.

40. A composition comprising hydrocarbons produced using the system as claimed in any of claims 1-27, or using the method as claimed in any of claims 28-39.

41. A transportation fuel made from the composition claimed in claim 40.

42. A system for heating a subsurface formation, comprising:

a first elongated heater in a first opening in the formation;

a second elongated heater in a second opening in the formation; and

wherein at least a portion of the second elongated heater is electrically coupled to at least a portion of the first elongated heater.

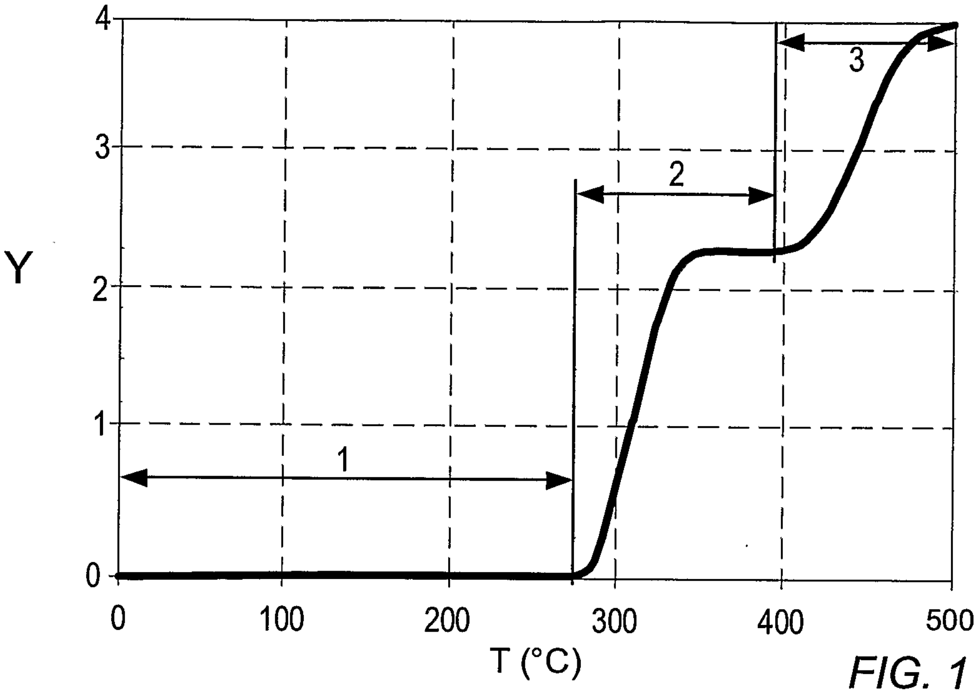

4
3
2
1
0
Y
0
100
200
300
400
500
T (°C)
1
2
3

FIG. 1

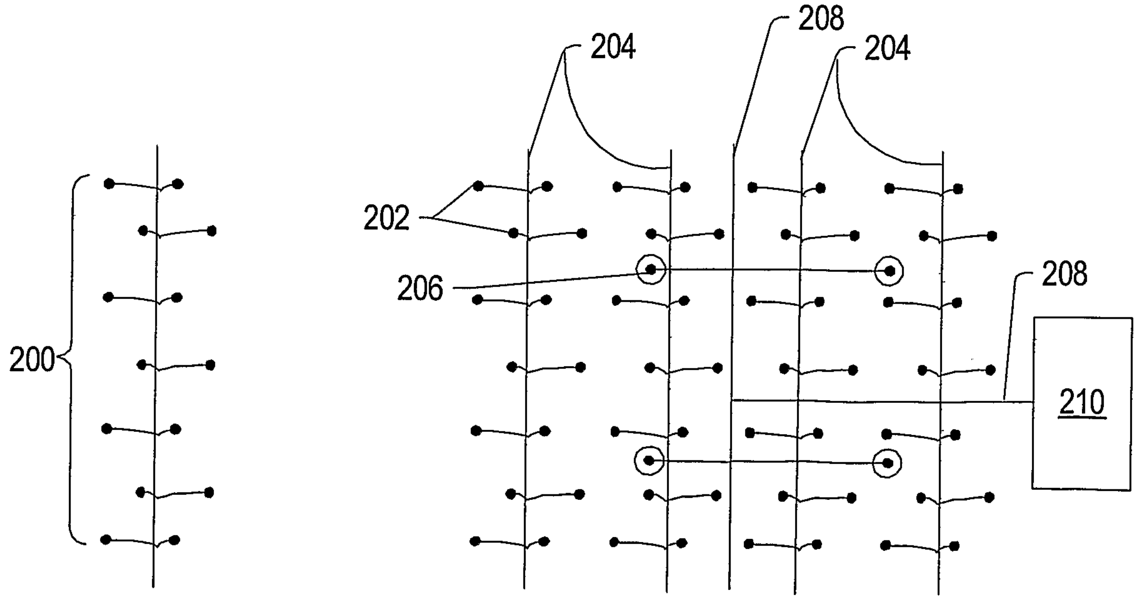

204
208
204
202
206
208
200
210

FIG. 2

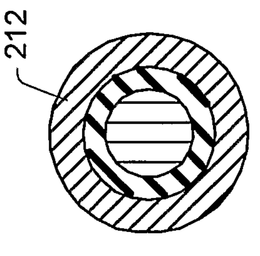


FIG. 4

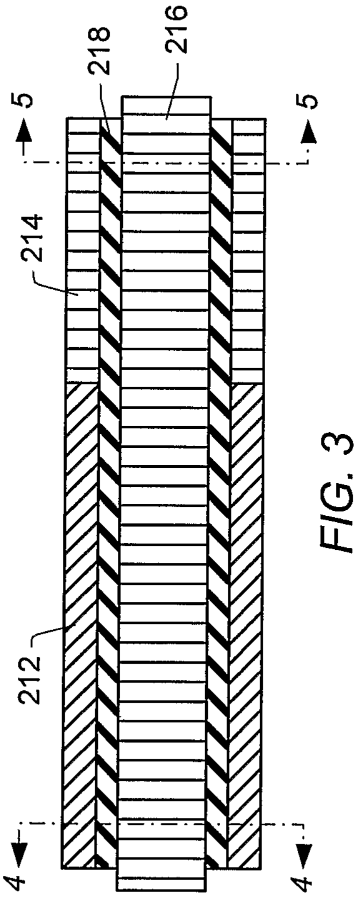


FIG. 3

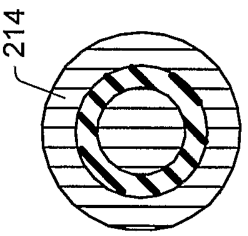


FIG. 5

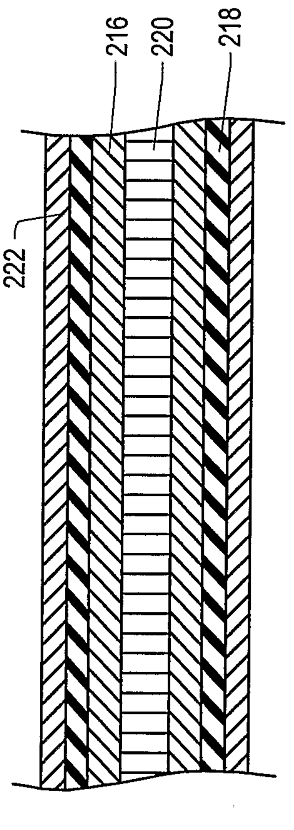


FIG. 6A

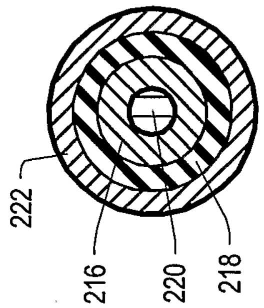


FIG. 6B

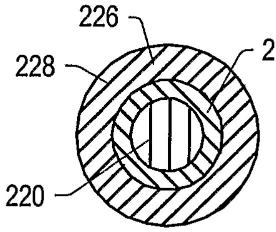


FIG. 7

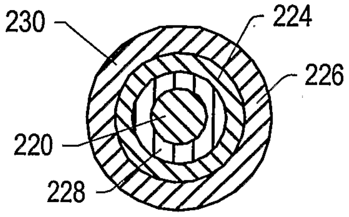


FIG. 8

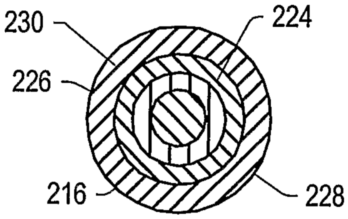


FIG. 9

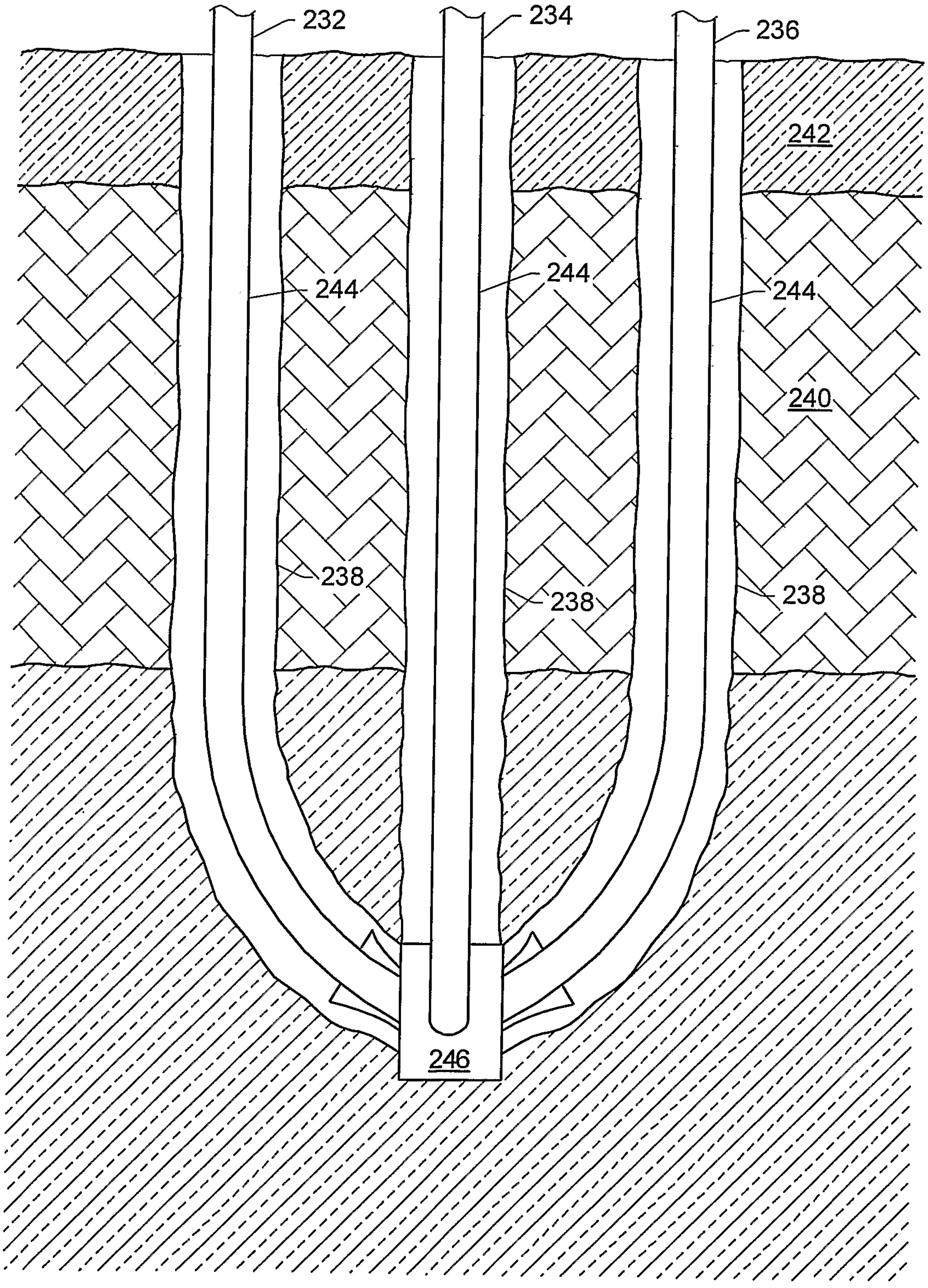


FIG. 10

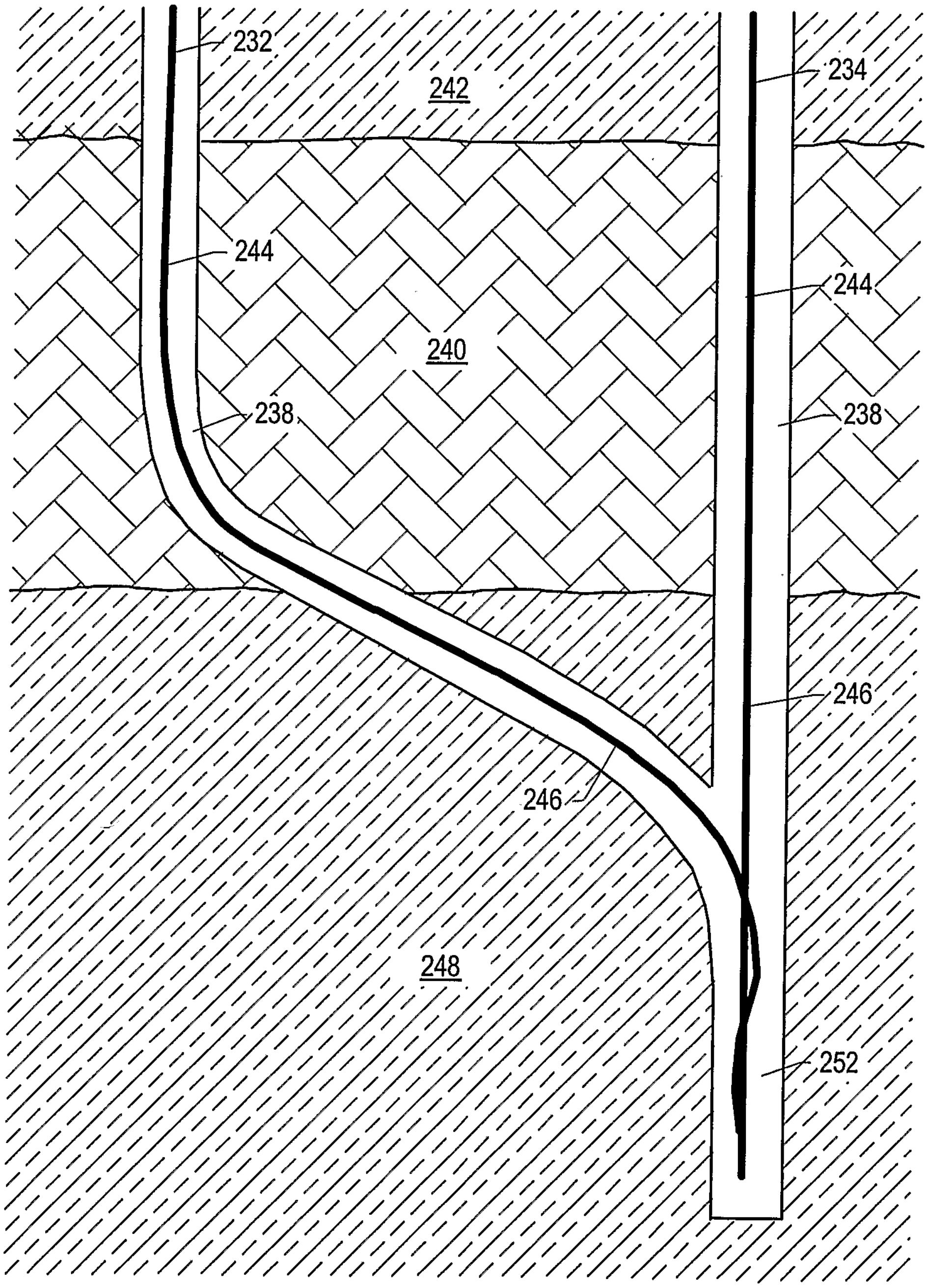


FIG. 11

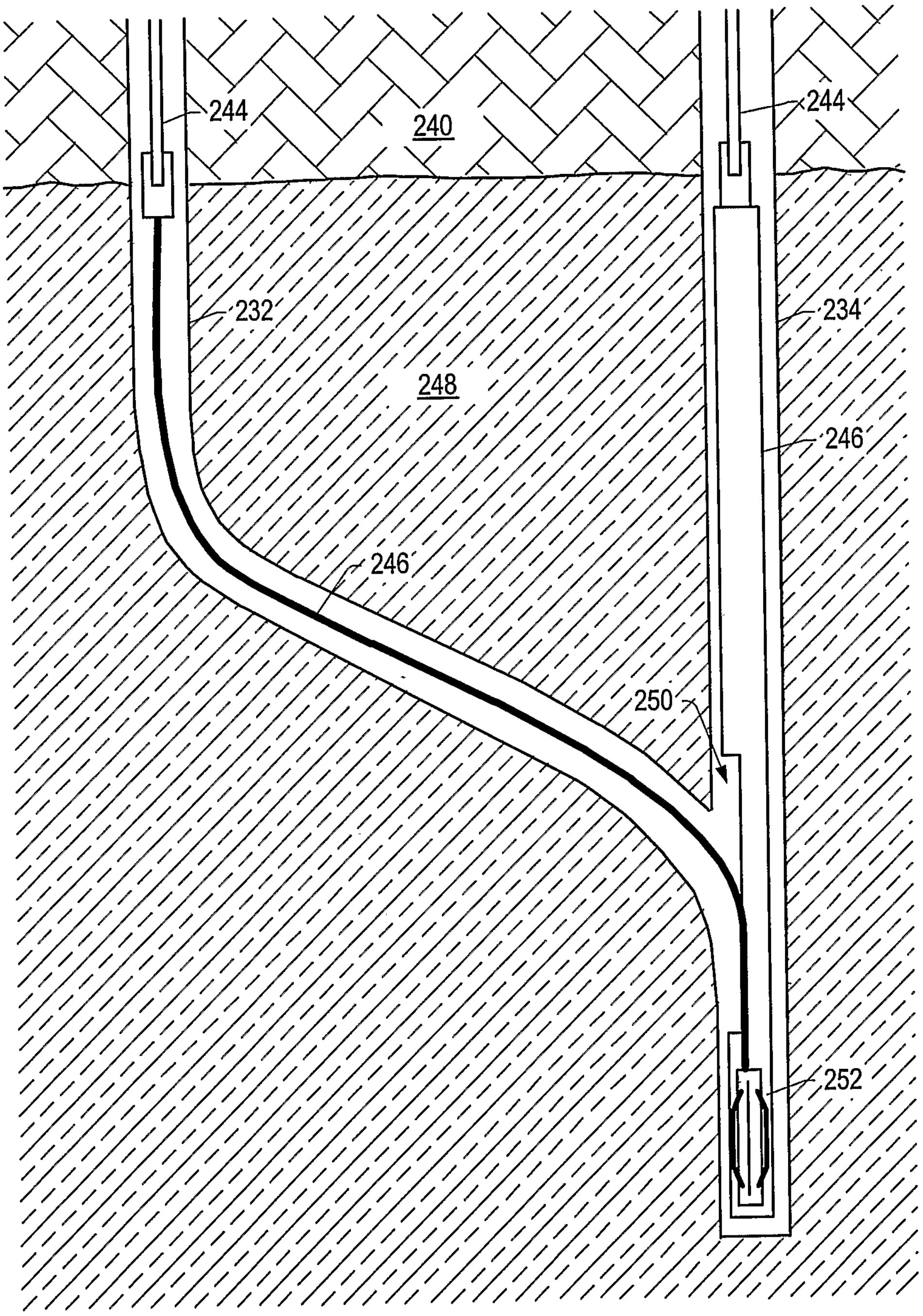


FIG. 12

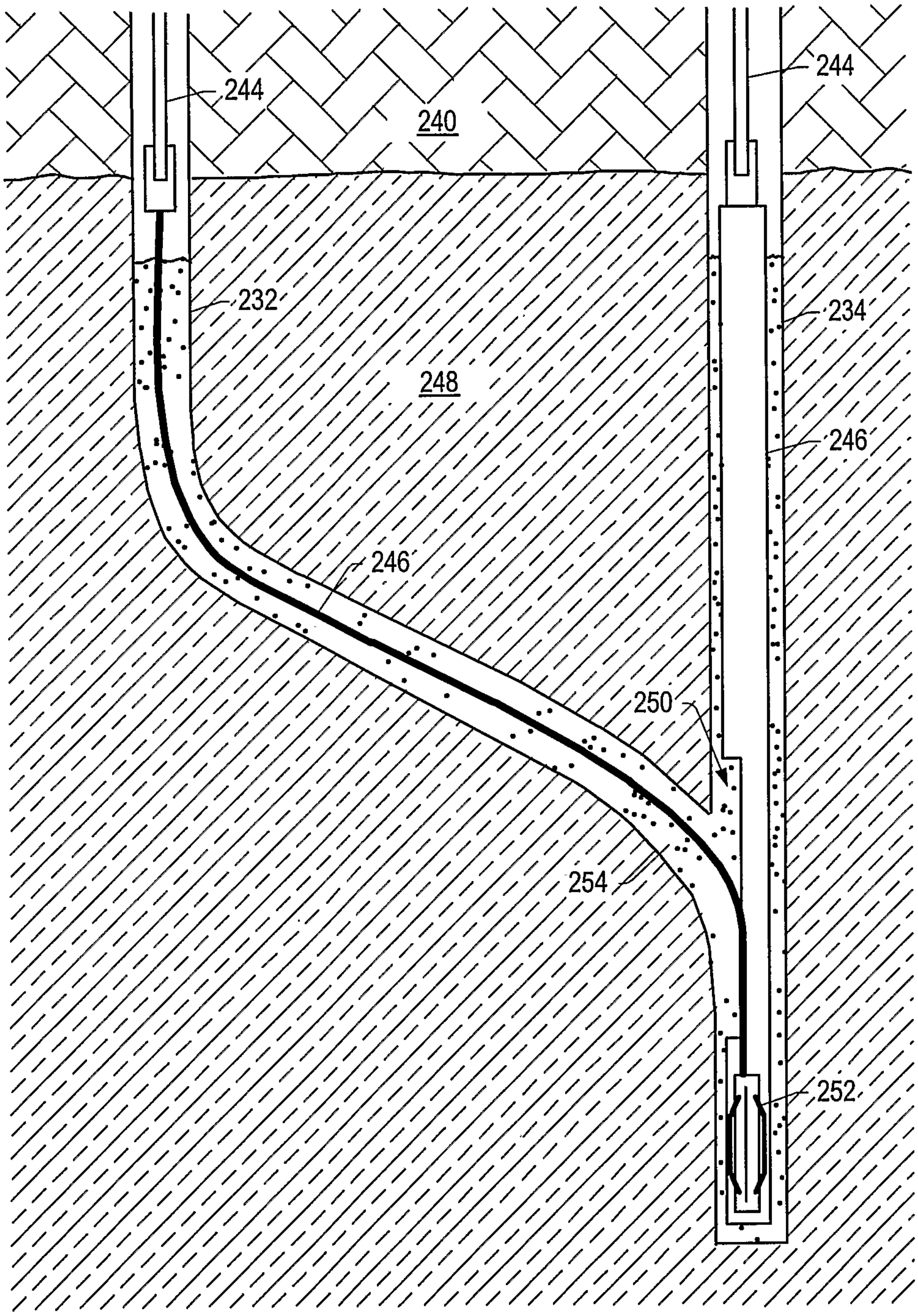


FIG. 13

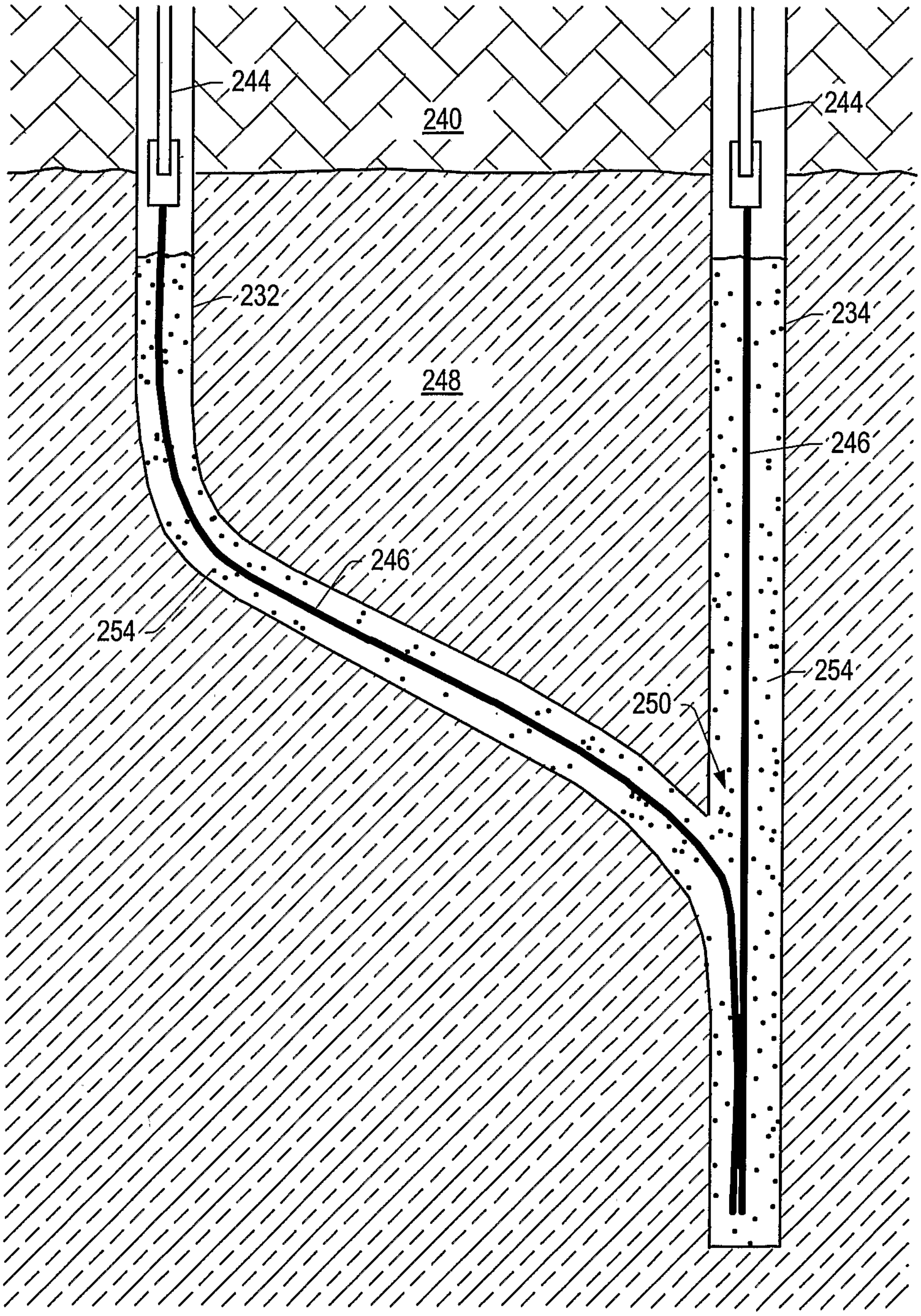


FIG. 14

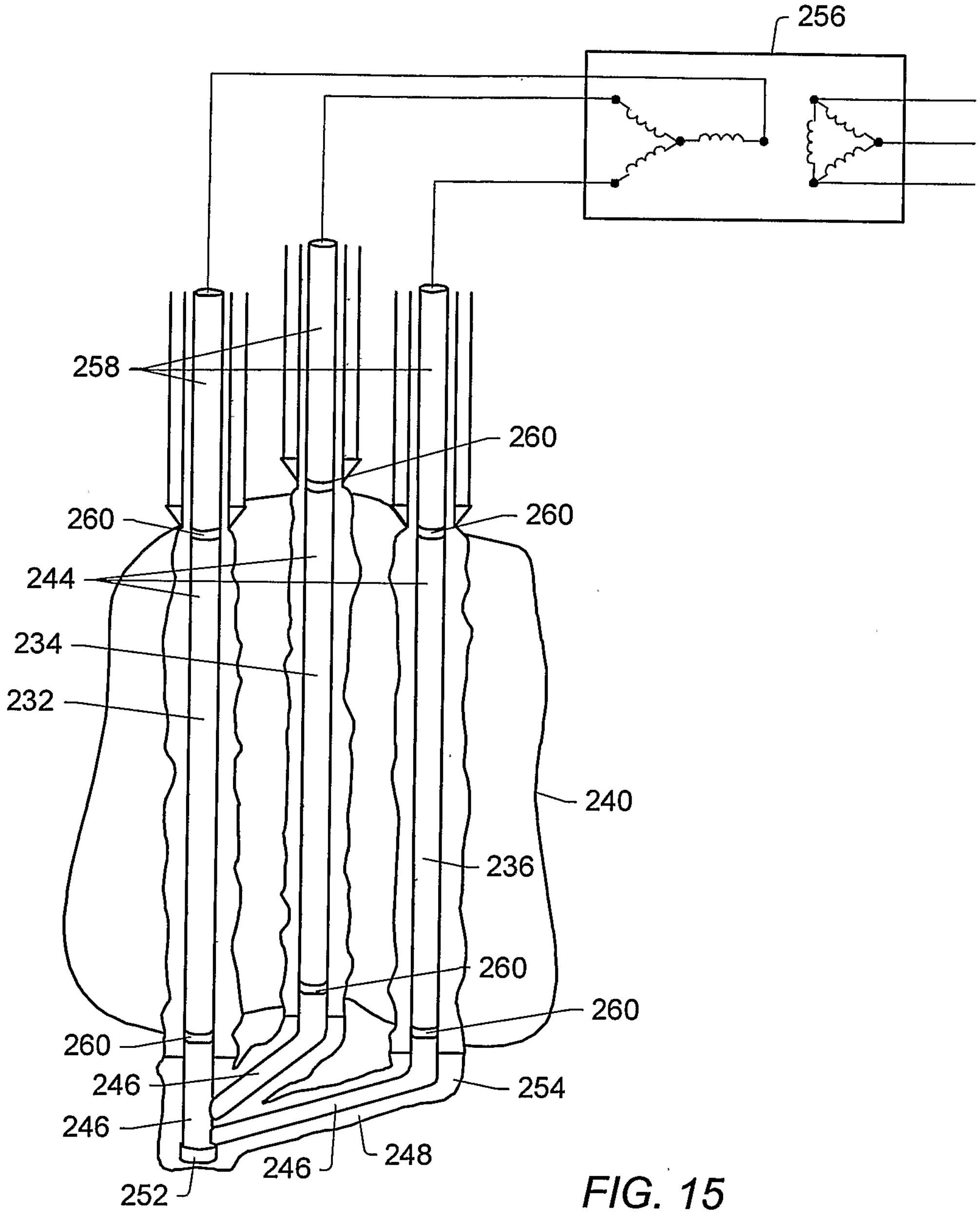

256
258
260
260
260
244
234
232
240
236
260
260
260
246
246
254
246
248
252

FIG. 15

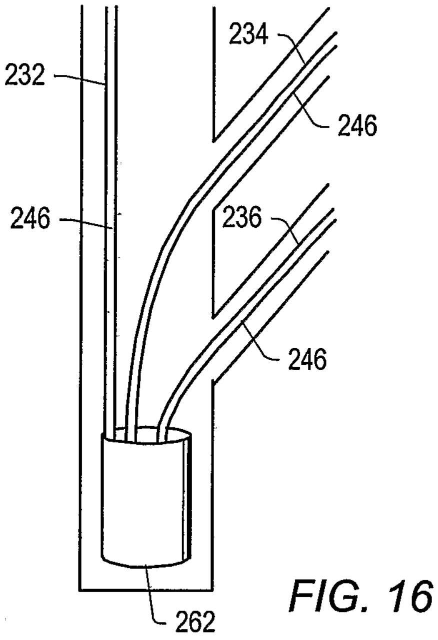


FIG. 16

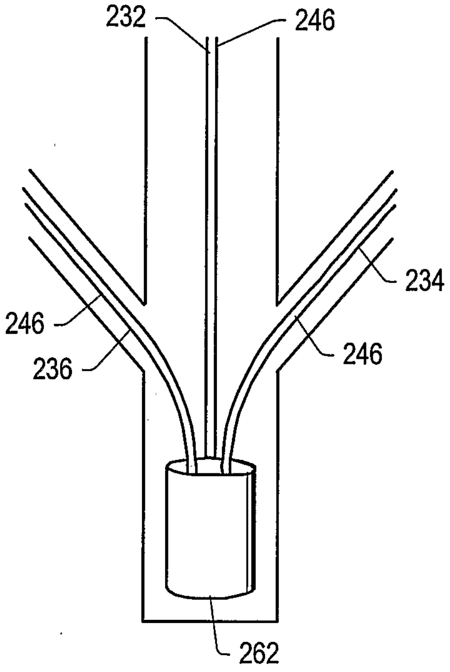


FIG. 17

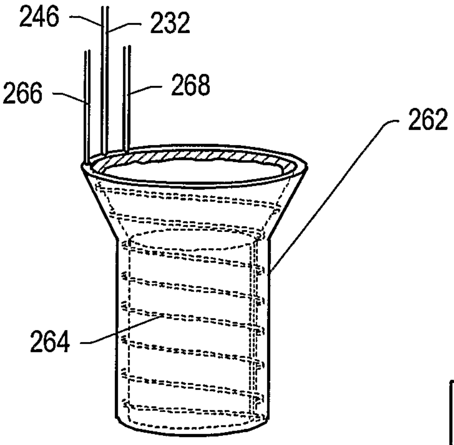


FIG. 18

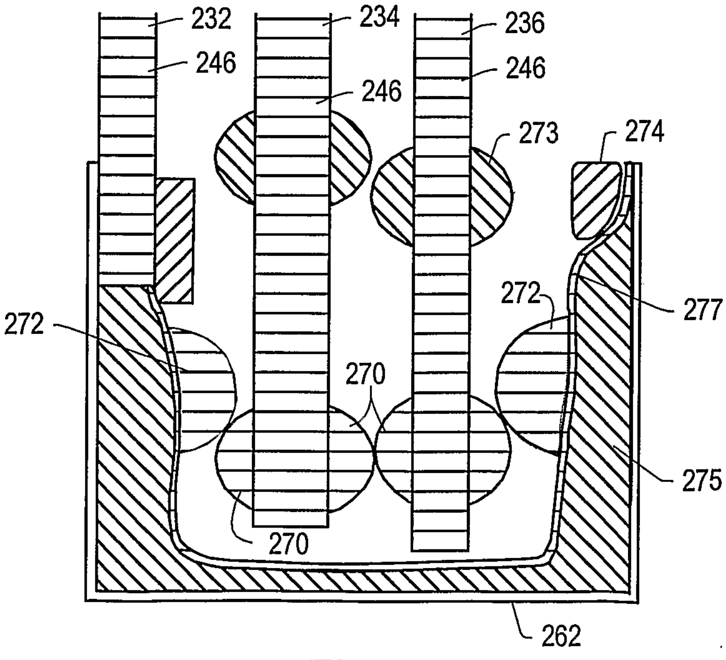


FIG. 19

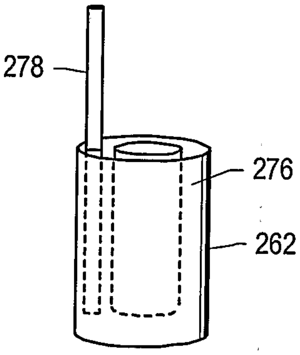


FIG. 20

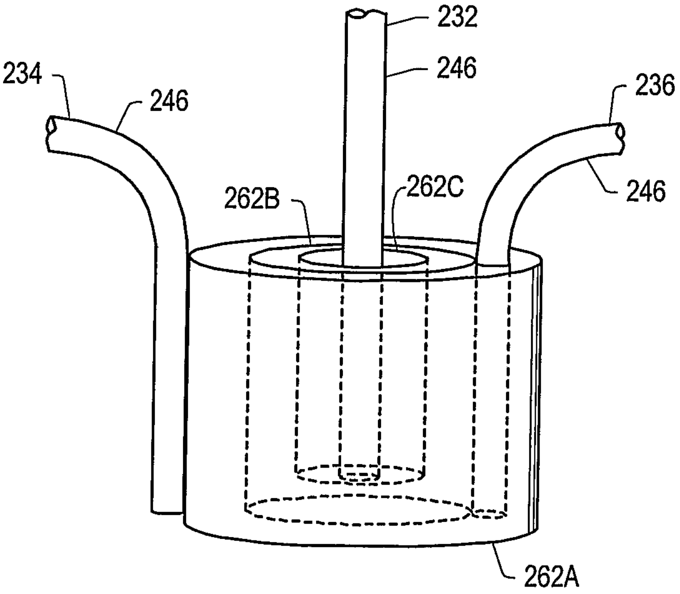


FIG. 21

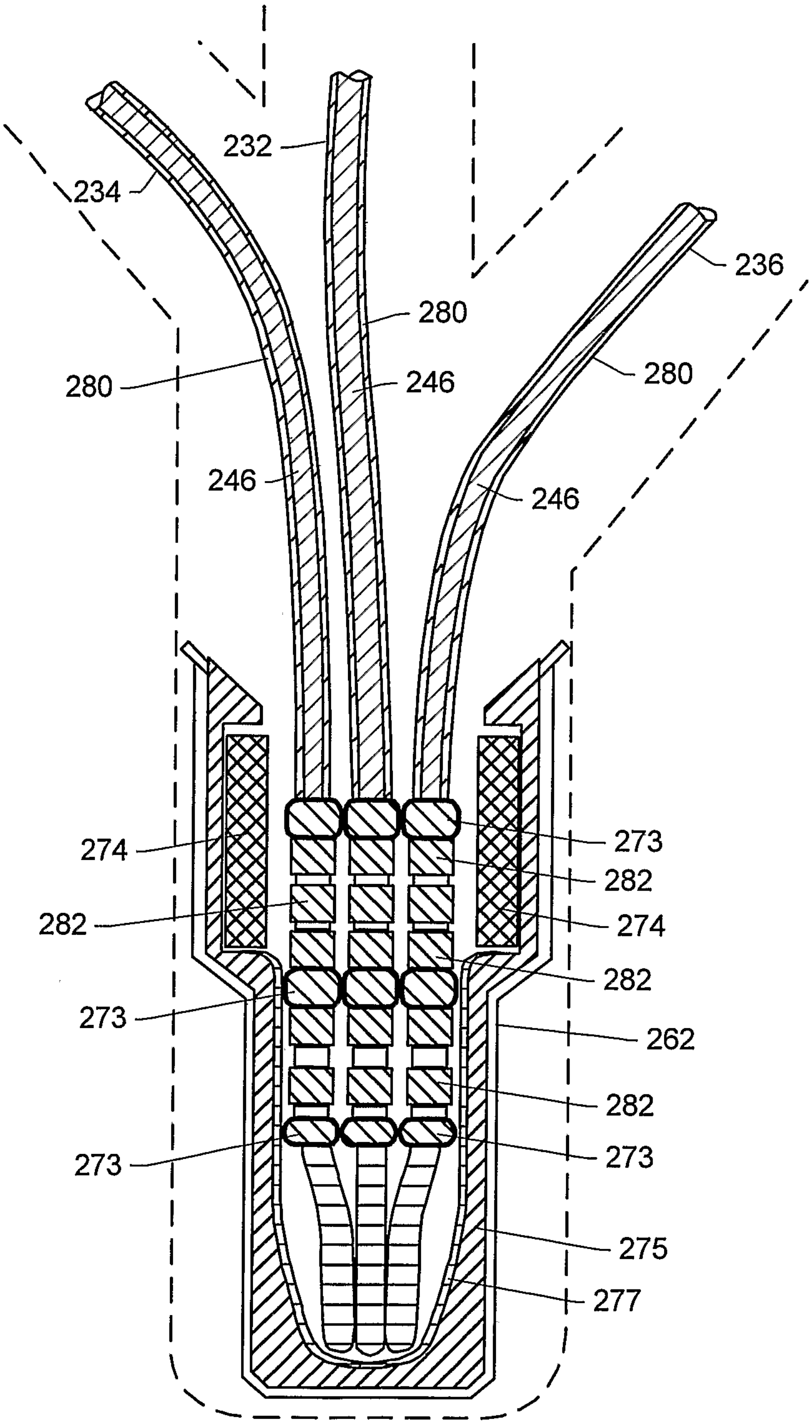

234
232
236
280
280
280
246
246
246
274
273
282
282
274
282
273
262
282
273
273
275
277

FIG. 22

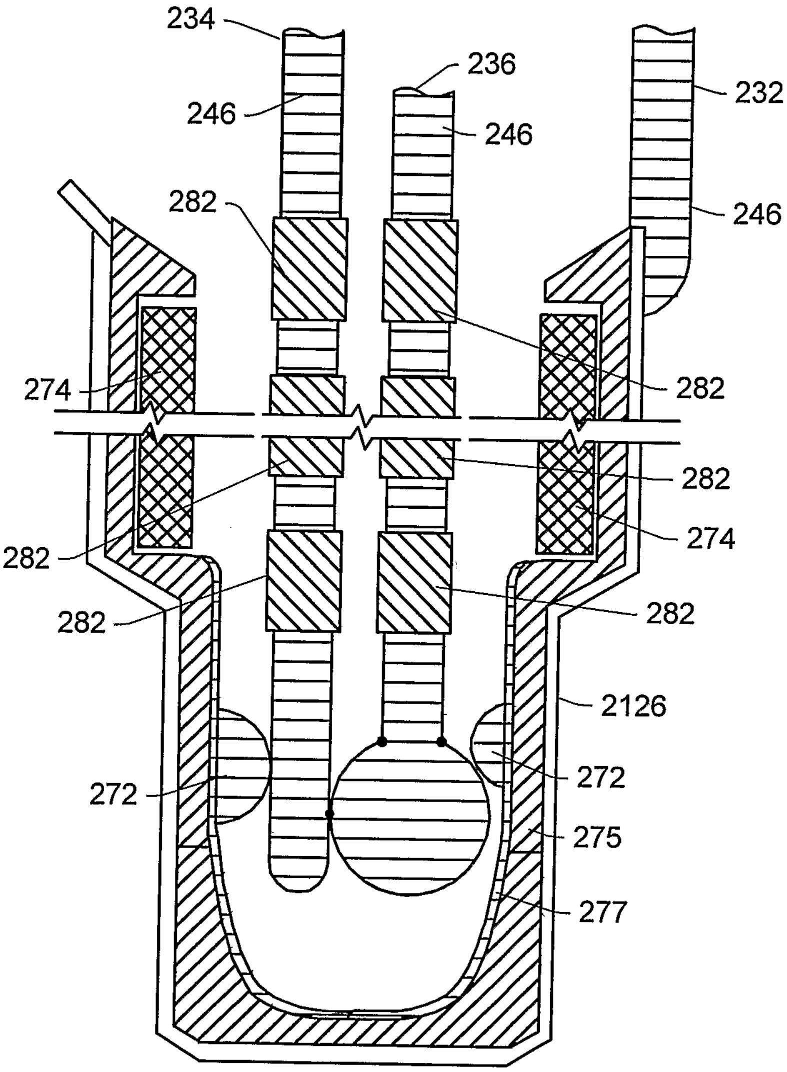

234
236
232
246
246
246
282
282
274
282
274
282
282
282
2126
272
272
275
277

FIG. 23

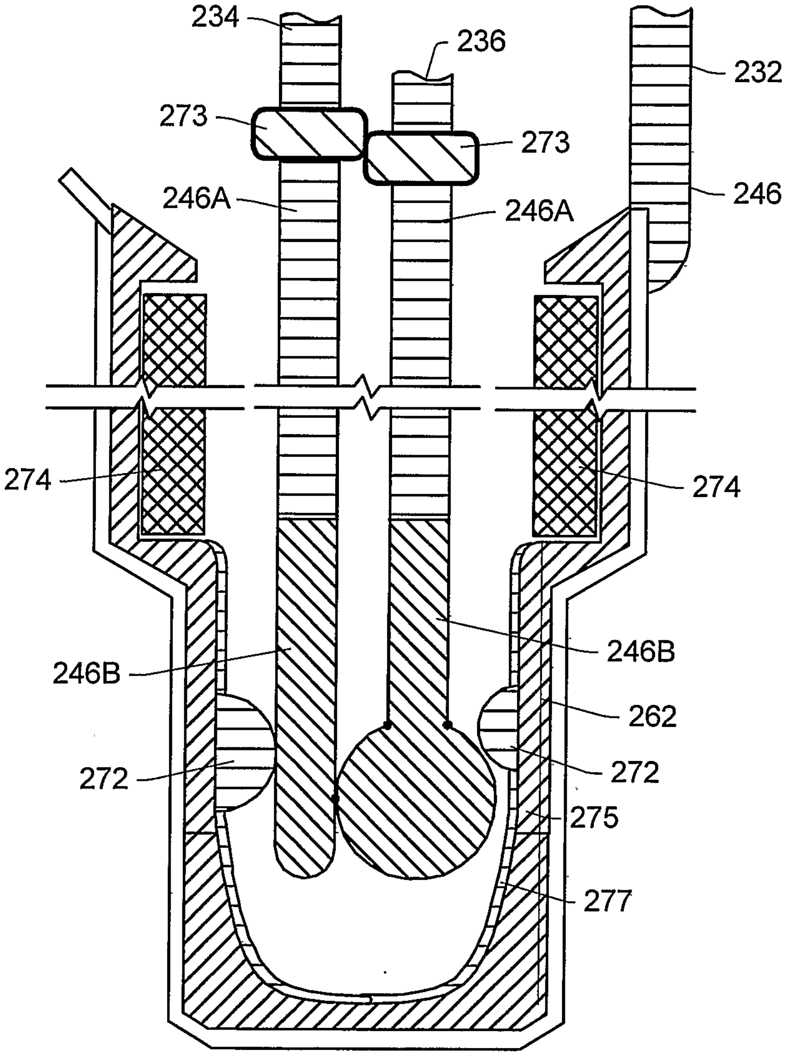

234
236
232
273
273
246A
246A
246
274
274
246B
246B
262
272
272
275
277

FIG. 24

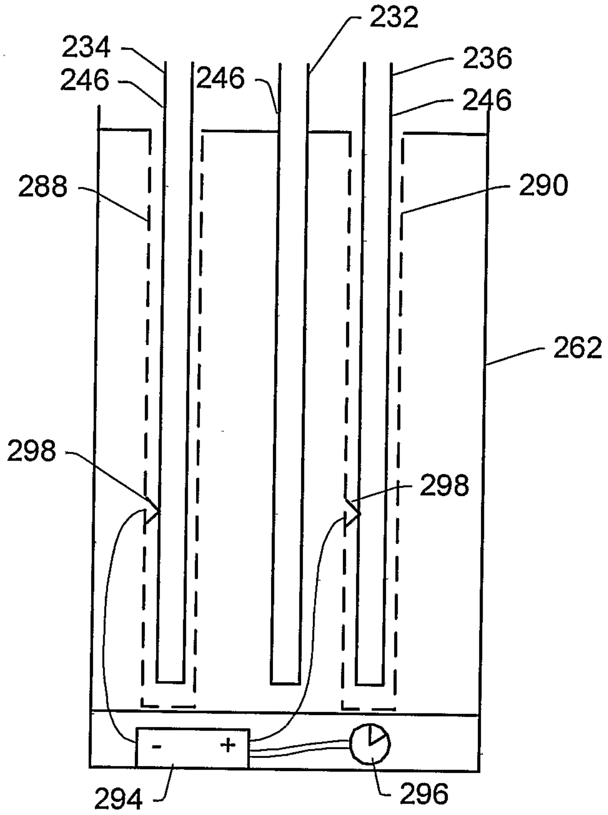

232
234
246
246
236
246
288
290
262
298
298
-
+
294
296

FIG. 25

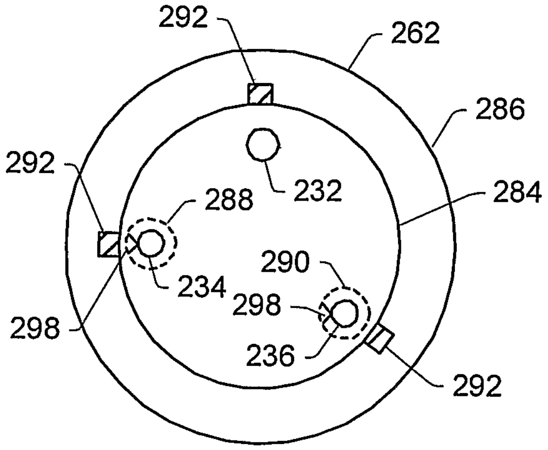

292
262
286
292
232
284
288
234
290
298
298
236
292

FIG. 26

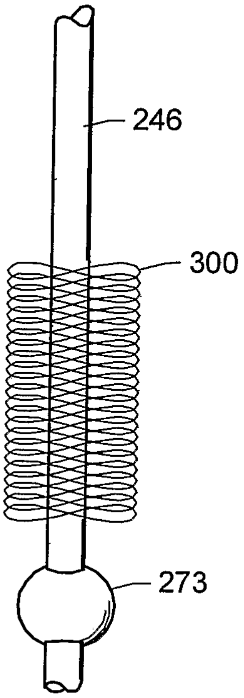


FIG. 27

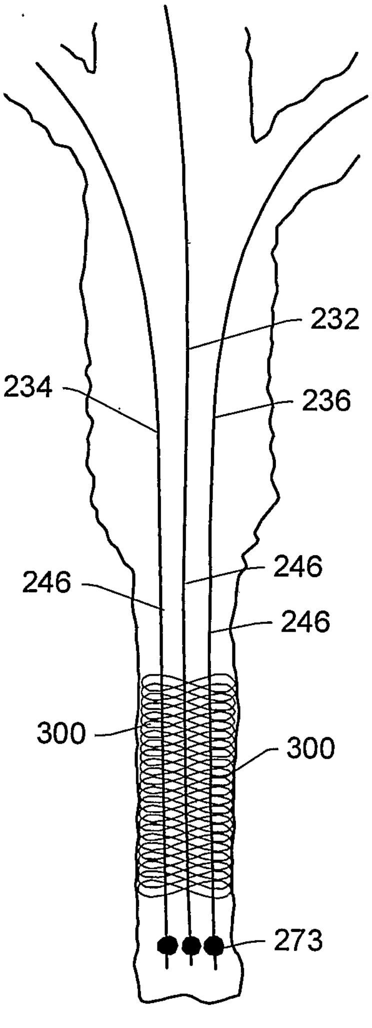


FIG. 28

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/015167

A. CLASSIFICATION OF SUBJECT MATTER
INV. E21B36/04 H01R4/08

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
E21B H01R

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 practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/140095 A1 (VINEGAR HAROLD J ET AL) 22 July 2004 (2004-07-22) paragraphs [0004], [0602], [0650], [0731], [0733]; figures 103,112,114,118	1-3,6,7, 28,39-42
A	WO 97/23924 A (RAYCHEM S.A; RAYCHEM LIMITED; BLUTEAU, DOMINIQUE; COLTIN, THIERRY; BRI) 3 July 1997 (1997-07-03) page 1, lines 3-8; figure 1b	8-17, 29-34
A	US 3 513 249 A (DAVID T. JAMES) 19 May 1970 (1970-05-19) column 1, lines 12-18,43-45; figures 2,3 column 3, lines 2-4	15-21, 35,36
A	US 3 529 075 A (HARRISON M. MCDONALD) 15 September 1970 (1970-09-15) column 1, lines 14-22; figure 1	15-21, 35,36
	-/--	

☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search 22 August 2006	Date of mailing of the international search report 29/08/2006
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Georgescu, M

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2006/015167

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3 542 276 A (DAVID T. JAMES) 24 November 1970 (1970-11-24) column 1, lines 4-7; figure 2 -----	15-21, 35,36

Form PCT/ISA/210 (continuation of second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2006/015167

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 2004140095	A1	22-07-2004	NONE	
WO 9723924	A	03-07-1997	NONE	
US 3513249	A	19-05-1970	NONE	
US 3529075	A	15-09-1970	NONE	
US 3542276	A	24-11-1970	NONE	