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(54) Title: UPGRADING AND MINING OF COAL

(57) Abstract: A method for treating a coal formation to alter properties of coal in the formation is provided. In one embodiment, heat from one or more heaters may be provided to at least a portion of the formation. Heat may be allowed to transfer from the one or more heaters to a part of the formation. In certain embodiments, the heat from the one or more heaters may pyrolyze at least some hydrocarbons within the part of the formation. The method may include producing a fluid from the formation. In some embodiments, the produced fluid may include at least some pyrolyzed hydrocarbons from the formation. In an embodiment, coal may be produced from the formation.



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**UPGRADING AND MINING OF COAL****BACKGROUND OF THE INVENTION**1. **Field of the Invention**

The present invention generally relates to production of useful materials from coal. Some embodiments of the present invention generally relate to methods and systems for upgrading of hydrocarbons within a coal formation.

2. **Description of Related Art**

Hydrocarbons obtained from subterranean (e.g., sedimentary) formations are often used as energy resources, as feedstocks, and as consumer products. Concerns over depletion of available hydrocarbon resources and declining overall quality of produced hydrocarbons have led to development of processes for more efficient recovery, processing and/or use of available hydrocarbon resources. An in situ conversion process may be used to alter hydrocarbon containing material in a treatment area of a formation. Chemical and/or physical properties of hydrocarbon material within 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 within 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.

Coal is often mined for use as a fuel within an electricity generating power plant. A significant number of coal formations are not suitable for economical mining. For example, mining coal from steeply dipping coal seams, from relatively thin coal seams (e.g., less than about 1 meter thick), and/or from deep coal seams may not be economically feasible. Deep coal seams include coal seams that are at, or extend to, depths of greater than about 3000 feet (about 914 m) below surface level. The energy conversion efficiency of burning coal to generate electricity is relatively low as compared to fuels such as natural gas. Also, burning coal to generate electricity may generate significant amounts of carbon dioxide, oxides of sulfur, and oxides of nitrogen that are released into the atmosphere.

There has been a significant amount of effort to develop methods and systems to economically produce hydrocarbons, hydrogen, and/or other products from coal formations. At present, however, there are still many coal formations from which hydrocarbons, hydrogen, and/or other products cannot be economically produced. Conventional extraction techniques may not be appropriate for all formations. In some formations, rich hydrocarbon containing material may be positioned in layers that are too thin to be economically extracted using conventional methods. An in situ conversion process may alter hydrocarbon containing material in a treatment area of a formation. Upon application of heat, hydrocarbon material such as coal may be converted and/or upgraded, thereby accelerating a process that would occur naturally over geological time.

**SUMMARY OF THE INVENTION**

In an embodiment, heat may be provided to a coal formation to utilize coal. Hydrocarbons within the coal formation may be converted to a mixture of relatively high quality hydrocarbon products, hydrogen, and/or other

products may be produced from the formation. Hydrocarbons, hydrogen, and other formation fluids may be removed from the formation through one or more production wells.

Application of heat to a coal formation may alter properties of coal in the formation. In some embodiments, portions of the coal formation may be converted to a higher rank of coal. Application of heat may reduce water content and/or volatile compound content of coal in the coal formation. Formation fluids (e.g., water and/or volatile compounds) may be removed in a vapor phase. In other embodiments, formation fluids may be removed in liquid and vapor phases or in a liquid phase. Temperature and pressure in at least a portion of the formation may be controlled during pyrolysis to yield improved products from the formation. After application of heat, coal may be produced from the formation.

### **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 of the preferred embodiments and upon reference to the accompanying drawings in which:

FIG. 1 depicts a diagram that presents several properties of kerogen resources.

FIG. 2 depicts an illustration of stages of heating a coal formation.

FIG. 3 depicts an embodiment of a heat source pattern.

FIG. 4 depicts an embodiment of a heater well.

FIG. 5 depicts an embodiment of a heater well.

FIG. 6 depicts an embodiment of a heater well.

FIG. 7 illustrates a schematic of an elevated view of multiple heaters branched from a single well in a coal formation.

FIG. 8 depicts an embodiment of heater wells located in a coal formation.

FIG. 9 depicts an embodiment of a pattern of heater wells in a coal formation.

FIG. 10 depicts an embodiment of a pattern of heat sources and production wells in a coal formation.

FIG. 11 depicts a plan view representation of an embodiment of treatment areas formed by perimeter barriers.

FIG. 12 depicts a cross-sectional representation of the in situ experimental field test.

FIG. 13 depicts locations of heat sources and wells in an experimental field test.

FIG. 14 depicts temperature versus time in the experimental field test.

FIG. 15 depicts temperature versus time in the experimental field test.

FIG. 16 depicts volume of oil produced from the experimental field test as a function of time.

FIG. 17 depicts volume of gas produced from a coal formation in the experimental field test as a function of time.

FIG. 18 depicts carbon number distribution of fluids produced from the experimental field test.

FIG. 19 depicts weight percentages of various fluids produced from a coal formation for various heating rates in laboratory experiments.

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 OF THE INVENTION**

5 The following description generally relates to systems and methods for treating a coal formation. Such formations may be treated to yield relatively high quality hydrocarbon products, hydrogen, high rank coal, and other products. Application of heat to a coal formation may convert and/or upgrade a portion of the coal formation, thereby accelerating a process that would occur naturally over geological time.

10 "Hydrocarbons" are molecules formed primarily by carbon and hydrogen atoms. "Hydrocarbon containing mixtures" may include hydrocarbons, as well as, other elements, such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur. Hydrocarbon containing formations may include, but are not limited to, kerogen, bitumen, pyrobitumen, oils, natural mineral waxes, and asphaltites. Hydrocarbon containing mixtures may be located within or adjacent to mineral matrices within the earth. Matrices may include, but are not limited to, sedimentary rock, sands, silicilytes, carbonates, diatomites, and other porous media. "Hydrocarbon containing  
15 fluids" are fluids that include hydrocarbons. Hydrocarbon containing fluids may include, entrain, or be entrained in non-hydrocarbon fluids (e.g., hydrogen ("H<sub>2</sub>"), nitrogen ("N<sub>2</sub>"), 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. An "overburden" and/or an "underburden" includes one or more different  
20 types of impermeable materials. For example, overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate (i.e., an impermeable carbonate without hydrocarbons). In some embodiments of in situ conversion processes, an overburden and/or an 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  
25 overburden and/or underburden. For example, an underburden may contain coal. In some cases, the overburden and/or underburden may be somewhat permeable.

"Kerogen" is a solid, insoluble hydrocarbon that has been converted by natural degradation (e.g., by diagenesis) and that principally contains carbon, hydrogen, nitrogen, oxygen, and sulfur. Coal is an example of a kerogen. "Oil" is a fluid containing a mixture of condensable hydrocarbons.

30 The terms "formation fluids" and "produced fluids" refer to fluids removed from a coal formation and may include pyrolyzation fluid, synthesis gas, mobilized hydrocarbon, and water (steam). Formation fluids may include hydrocarbon fluids as well as non-hydrocarbon fluids.

"Carbon number" refers to a number of carbon atoms within a molecule. A hydrocarbon fluid may include various hydrocarbons having varying numbers of carbon atoms. The hydrocarbon fluid may be described by a  
35 carbon number distribution. Carbon numbers and/or carbon number distributions may be determined by true boiling point distribution and/or gas-liquid chromatography.

A "heat source" is any system for providing heat to at least a portion of a formation substantially by conductive and/or radiative heat transfer. For example, a heat source may include electric heaters such as an insulated conductor, an elongated member, and a conductor disposed within a conduit. A heat source may also  
40 include heat sources that generate heat by burning a fuel external to or within a formation, such as surface burners, downhole gas burners, flameless distributed combustors, and natural distributed combustors. In addition, it is

envisioned that in some embodiments heat provided to or generated in one or more heat sources may be supplied by other sources of energy. The other sources of energy may directly heat a formation, or the energy may be applied to a transfer media that directly or indirectly heats the formation. It is to be understood that one or more heat sources that are applying heat to a formation may use different sources of energy. For example, for a given formation some heat sources may supply heat from electric resistance heaters, some heat sources may provide heat from combustion, and some heat sources may provide heat from one or more other energy sources (e.g., chemical reactions, solar energy, wind energy, biomass, or other sources of renewable energy). A chemical reaction may include an exothermic reaction (e.g., an oxidation reaction). A heat source may include a heater that provides heat to a zone proximate and/or surrounding a heating location such as a heater well.

A "heater" is any system 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 (e.g., natural distributed combustors), and/or combinations thereof. A "unit of heat sources" refers to a number of heat sources that form a template that is repeated to create a pattern of heat sources within a 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 other cross-sectional shapes (e.g., circles, ovals, squares, rectangles, triangles, slits, or other regular or irregular shapes). As used herein, the terms "well" and "opening," when referring to an opening, in the formation may be used interchangeably with the term "wellbore."

"Natural distributed combustor" refers to a heater that uses an oxidant to oxidize at least a portion of the carbon in the formation to generate heat, and wherein the oxidation takes place in a vicinity proximate a wellbore. Most of the combustion products produced in the natural distributed combustor are removed through the wellbore.

"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. The term "self-controls" refers to controlling an output of a heater without external control of any type.

"Pyrolysis" is the breaking of chemical bonds due to the application of heat. For example, pyrolysis may include transforming a compound into one or more other substances by heat alone. Heat may be transferred to a section of the formation to cause pyrolysis.

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

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

"Condensable hydrocarbons" are hydrocarbons that condense at 25 °C at one atmosphere absolute pressure. Condensable hydrocarbons may include a mixture of hydrocarbons having carbon numbers greater than 4.

"Non-condensable hydrocarbons" are hydrocarbons that do not condense at 25 °C and one atmosphere absolute pressure. Non-condensable hydrocarbons may include hydrocarbons having carbon numbers less than 5.

"Synthesis gas" is a mixture including hydrogen and carbon monoxide used for synthesizing a wide range of compounds. Additional components of synthesis gas may include water, carbon dioxide, nitrogen, methane, and other gases. Synthesis gas may be generated by a variety of processes and feedstocks.

"Dipping" refers to a formation that slopes downward or inclines from a plane parallel to the earth's surface, assuming the plane is flat (i.e., a "horizontal" plane). A "dip" is an angle that a stratum or similar feature

makes with a horizontal plane. A “steeply dipping” coal formation refers to a coal formation lying at an angle of at least 20° from a horizontal plane. “Down dip” refers to downward along a direction parallel to a dip in a formation. “Up dip” refers to upward along a direction parallel to a dip of a formation. “Strike” refers to the course or bearing of hydrocarbon material that is normal to the direction of dip.

5 “Subsidence” is a downward movement of a portion of a formation relative to an initial elevation of the surface.

“Thickness” of a layer refers to the thickness of a cross section of a layer, wherein the cross section is normal to a face of the layer.

10 “Upgrade” refers to increasing the quality of hydrocarbons. For example, upgrading coal may result in an increase in the rank of the coal.

Coal formations may include kerogen. Kerogen is composed of organic matter that has been transformed due to a maturation process. The maturation process for kerogen may include two stages: a biochemical stage and a geochemical stage. The biochemical stage typically involves degradation of organic material by aerobic and/or anaerobic organisms. The geochemical stage typically involves conversion of organic matter due to temperature changes and significant pressures. During maturation, oil and gas may be produced as the organic matter of the kerogen is transformed.

15 As shown in FIG. 1, the van Krevelen depicts the maturation sequence for kerogen that typically occurs over geological time due to temperature and pressure. In addition, the van Krevelen diagram classifies various natural deposits of kerogen. For example, kerogen may be classified into four distinct groups: type I, type II, type III, and type IV, which are illustrated by the four branches of the van Krevelen diagram. Classification of kerogen type may depend upon precursor materials of the kerogen. The precursor materials transform over time into macerals. “Macerals” are microscopic structures in kerogen. The structures and properties of macerals are dependent on the precursor materials from which the macerals are derived.

20 A type I kerogen may be classified as an alginite, since type I kerogen developed primarily from algal bodies. Type I kerogen may result from deposits made in lacustrine environments. Type II kerogen may develop from organic matter that was deposited in marine environments. Type III kerogen may generally include vitrinite macerals. Vitrinite is derived from cell walls and/or woody tissues (e.g., stems, branches, leaves, and roots of plants). Type III kerogen may be present in most humic coals. Type III kerogen may develop from organic matter that was deposited in swamps. Type IV kerogen includes the inertinite maceral group. The inertinite maceral group is composed of plant material such as leaves, bark, and stems that have undergone oxidation during the early peat stages of burial diagenesis. Inertinite maceral is chemically similar to vitrinite, but has a high carbon and low hydrogen content.

25 The van Krevelen diagram depicted in FIG. 1 plots an atomic hydrogen to carbon ratio (y axis) versus an atomic oxygen to carbon ratio (x axis) for various types of kerogen. The van Krevelen diagram shows the maturation sequence for various types of kerogen that typically occurs over geologic time due to temperature, pressure, and biochemical degradation. This maturation sequence may be accelerated by heating in situ at a controlled rate and/or a controlled pressure.

30 If a formation containing kerogen in region 30 or region 32 is selected for in situ conversion, in situ thermal treatment may accelerate maturation of the kerogen along paths represented by arrows in FIG. 1. For example, region 30 kerogen may transform to region 32 kerogen and possibly then to region 34 kerogen. Region 32

kerogen may transform to region 34 kerogen. In situ conversion may expedite maturation of kerogen and allow production of valuable products from the kerogen. Region 36 may be a graphite region.

As kerogen undergoes maturation, the composition of the kerogen usually changes due to expulsion of volatile matter (e.g., carbon dioxide, methane, and oil) from the kerogen. Rank classifications of kerogen indicate the level to which kerogen has matured. For example, as kerogen undergoes maturation, the rank of kerogen increases. As rank increases, the volatile matter within, and producible from, the kerogen tends to decrease. In addition, the moisture content of kerogen generally decreases as the rank increases. At higher ranks, the moisture content may reach a relatively constant value. Higher rank kerogens that have undergone significant maturation, such as semi-anthracite or anthracite coal, tend to have a higher carbon content and a lower volatile matter content than lower rank kerogens such as lignite. In some embodiments, a carbon content of produced coal may be greater than about 87 weight % and/or a volatile matter content may be less than about 5 weight %.

Rank stages of coal formations include the following classifications, which are listed in order of increasing rank and maturity for type III kerogen: wood, peat, lignite, sub-bituminous coal, high volatile bituminous coal, medium volatile bituminous coal, low volatile bituminous coal, semi-anthracite, and anthracite. As rank increases, kerogen tends to exhibit an increase in aromatic nature.

Coal formations may be selected for in situ conversion based on properties of at least a portion of the formation. For example, a formation may be selected based on richness, thickness, and/or depth (i.e., thickness of overburden) of the formation. In addition, the types of fluids producible from the formation may be a factor in the selection of a formation for in situ conversion. In certain embodiments, the quality of the fluids to be produced may be assessed in advance of treatment. Assessment of the products that may be produced from a formation may generate significant cost savings since only formations that will produce desired products need to be subjected to in situ conversion. Properties that may be used to assess hydrocarbons in a formation include, but are not limited to, an amount of hydrocarbon liquids that may be produced from the hydrocarbons, a likely API gravity of the produced hydrocarbon liquids, vitrinite reflectance, an amount of hydrocarbon gas producible from the formation, and/or an amount of carbon dioxide and water that in situ conversion will generate.

For example, vitrinite reflectance is often related to a hydrogen to carbon atomic ratio of a kerogen and an oxygen to carbon atomic ratio of the kerogen, as shown by the dashed lines in FIG. 1. A van Krevelen diagram may be useful in selecting a resource for an in situ conversion process. Vitrinite reflectance of a kerogen in a coal formation may indicate which fluids are producible from a formation upon heating. For example, a vitrinite reflectance of approximately 0.5% to approximately 1.5% may indicate that the kerogen will produce a large quantity of condensable fluids. In addition, a vitrinite reflectance of approximately 1.5% to 3.0% may indicate a kerogen in region 34. If a coal formation having such kerogen is heated, a significant amount (e.g., a majority) of the fluid produced by such heating may include methane and hydrogen. The formation may be used to generate synthesis gas if the temperature is raised sufficiently high and a synthesis gas generating fluid is introduced into the formation.

Coal formations may have varied geometries and shapes. Conventional extraction techniques may not be appropriate for all formations. In some formations, rich hydrocarbon containing material may be positioned in layers that are too thin to be economically extracted using conventional methods. The rich coal formations typically occur in beds having thicknesses between about 0.2 m and about 8 m. These rich coal formations may include, but are not limited to, sapropelic coals (boghead, cannel coals, and/or torbanites). The hydrocarbon layers may yield from about 205 liters of oil per metric ton to about 1670 liters of oil per metric ton upon pyrolysis.

An in situ conversion process may alter hydrocarbon containing material in a treatment area of a formation. Upon application of heat, hydrocarbon material such as coal may be converted and/or upgraded, thereby accelerating a process that would occur naturally over geological time. Various properties of coal within a treatment area may be altered including, but not limited to, a heating value, a vitrinite reflectance, a moisture content, a volatile matter percentage, permeability, porosity, concentrations of various components in the coal such as sulfur, and/or a carbon percentage.

As a coal formation is heated, the coal may undergo several stages of heating as illustrated by FIG. 2. FIG. 2 depicts an example of yield (barrels of oil equivalent per ton) (y axis) of formation fluids from a coal formation versus temperature (°C) (x axis) of the formation.

Desorption of methane and vaporization of water occurs during in region 38 heating. Heating of the formation through region 38 may be performed as quickly as possible. For example, when a coal formation is initially heated, hydrocarbons in the formation may desorb adsorbed methane. The desorbed methane may be produced from the formation. If the coal formation is heated further, water within the coal formation may be vaporized. Water may occupy, in some coal formations, between about 10 % to about 50 % of the pore volume in the formation. In other formations, water may occupy larger or smaller portions of the pore volume. Water typically is vaporized in a formation between about 160 °C and about 285 °C for pressures of about 6 bars absolute to 70 bars absolute. In some embodiments, the vaporized water may produce wettability changes in the formation and/or increase 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 may be produced from the formation. In other embodiments, the vaporized water may be 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 may increase the storage space for hydrocarbons within the pore volume.

After region 38 heating, the formation may be heated further, such that a temperature within the formation reaches (at least) an initial pyrolyzation temperature (e.g., a temperature at the lower end of the temperature range shown as region 40). Hydrocarbons within the formation may be pyrolyzed throughout region 40. A pyrolysis temperature range may vary depending on types of hydrocarbons within the formation. A pyrolysis temperature range may include temperatures between about 250 °C and about 900 °C. A pyrolysis temperature range for producing desired products may extend through only a portion of the total pyrolysis temperature range. In some embodiments, a pyrolysis temperature range for producing desired products may include temperatures between about 250 °C to about 400 °C. If a temperature of hydrocarbons in a formation is slowly raised through a temperature range from about 250 °C to about 400 °C, production of pyrolysis products may be substantially complete when the temperature approaches 400 °C. 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 a pyrolysis temperature range.

In some in situ conversion embodiments, a temperature of the hydrocarbons to be subjected to pyrolysis may not be slowly increased throughout a temperature range from about 250 °C to about 400 °C. The hydrocarbons in the formation may be heated to a desired temperature (e.g., about 325 °C). Other temperatures may be selected as the desired temperature. Superposition of heat from heat sources may allow 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



hydrocarbons may be maintained substantially at the desired temperature until pyrolysis declines such that production of desired formation fluids from the formation becomes uneconomical.

Formation fluids including pyrolyzation fluids may be produced from the formation. The pyrolyzation fluids may include, but are not limited to, hydrocarbons, hydrogen, carbon dioxide, carbon monoxide, hydrogen sulfide, ammonia, nitrogen, water, and mixtures thereof. As the temperature of the formation increases, the amount of condensable hydrocarbons in the produced formation fluid tends to decrease. At high temperatures, the formation may produce mostly methane and/or hydrogen. If a coal 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. In some embodiments, a significant portion of remaining carbon in the formation can be produced from the formation in the form of synthesis gas upon introduction of additional heat and a synthesis gas generating fluid. Synthesis gas generation may take place during region 42 heating.

In some embodiments, a coal formation may be mined after region 40 heating without undergoing a synthesis gas generation phase. In some embodiments, a coal formation may be mined after undergoing synthesis gas generation during region 42 heating. The processing of the coal formation may mature remaining coal in the formation towards anthracitic coal. In some embodiments, the mined material may be used for metallurgical purposes such as a fuel for generating high temperatures during production of steel. Pyrolysis of a coal formation may increase a rank of the coal. After pyrolysis, the coal may be transformed to a coal having characteristics of anthracite. A spent coal formation may have a thickness of 30 m or more. In comparison, anthracite coal seams that are typically mined for metallurgical uses are typically about one meter or less in thickness.

For example, coal within a treatment area may be considered a bituminous coal prior to treatment. Application of heat may alter the bituminous coal to form an anthracite coal. An anthracite coal has a lower moisture content, a higher heating value, and a higher carbon weight percent. In certain embodiments, anthracite coal may be used in metallurgical processing. Typically, anthracite coal is found in thin coal seams of a few meters thickness. The in situ conversion process may generate an anthracite seam from a thick bituminous coal that is thicker than would be produced naturally.

Coal altered by an in situ conversion process may have a high permeability and porosity. At least some of the coal heated using the in situ conversion process may, in certain embodiments, contain several fractures. In some instances, at least a portion of the coal may be friable or in a powdered form. In some embodiments, coal treated with an in situ conversion process may be easily mined using an underground automated or robotic system to mine coal as a powder or as a slurry. For example, water jetting may be used to remove at least some coal in a slurry. In some embodiments, an overburden may be removed by earth moving equipment after sufficient time has passed to allow the treated formation to cool to a temperature that allows for safe operation. In some embodiments, tunnels may be formed to coal that has been treated using an in situ process. Traditional mining equipment may be used to reach and remove the coal.

Coal produced as a powder or in a slurry may be used in various processes including, but not limited to, directly combusting coal at the surface for use as an energy source and/or slurrying the coal and transporting the coal for sale as an energy fuel. For example, a first fluid may be injected into a portion of the formation that has been treated using an in situ conversion process. The first fluid may include water. The first fluid may break and/or

fragment the coal in the formation into relatively small pieces. The relatively small pieces may combine with the first fluid to form a slurry. The slurry may be removed or produced from the formation. The slurry may be treated in a surface facility to separate the first fluid from the relatively small pieces of coal. The coal pieces may be treated in a refining or extraction process in a surface facility.

5        Such coal may be used as an activated carbon filter to remove components from various water and/or air streams within an in situ conversion process site and/or at external sites. The coal may alternately be used as an adsorbent (which may further upgrade the coal as a fuel) followed by combustion of the coal for power, as an intermediate in dyes (e.g., anthraquinone), as a fuel, and/or in metallurgical processes. Treating coal with an in situ conversion process may alter the coal such that an economic value of the coal increases and/or the costs associated with mining the coal decrease.

10        Total energy content of fluids produced from a coal formation may stay relatively constant throughout pyrolysis. 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.

15        Heating a coal formation may include providing a large amount of energy to heat sources located within the formation. Coal formations may also contain some water. A significant portion of energy initially provided to a formation may be used to heat water within the formation. An initial rate of temperature increase may be reduced by the presence of water in the formation. Excessive amounts of heat and/or time may be required to heat a formation having a high moisture content to a temperature sufficient to pyrolyze hydrocarbons in the formation. In certain embodiments, water may be inhibited from flowing into a formation subjected to in situ conversion. A formation to be subjected to in situ conversion may have a low initial moisture content. The formation may have an initial moisture content that is less than about 15 weight %. Some formations that are to be subjected to in situ conversion may have an initial moisture content of less than about 10 weight %. Other formations that are to be processed using an in situ conversion process may have initial moisture contents that are greater than about 15 weight %. Formations with initial moisture contents above about 15 weight % may incur significant energy costs to remove the water that is initially present in the formation during heating to pyrolysis temperatures.

20        A coal formation may include multiple layers. Such layers may include hydrocarbon containing layers, as well as layers that are hydrocarbon free or have relatively low amounts of hydrocarbons. Conditions during formation may determine the thickness of hydrocarbon and non-hydrocarbon layers in a coal formation. A coal formation to be subjected to in situ conversion will typically include at least one hydrocarbon containing layer having a thickness sufficient for economical production of formation fluids. Richness of a hydrocarbon containing layer may be a factor used to determine if a formation will be treated by in situ conversion. A thin and rich hydrocarbon layer may be able to produce significantly more valuable hydrocarbons than a much thicker, less rich hydrocarbon layer. Producing hydrocarbons from a formation that is both thick and rich is desirable.

25        FIG. 3 shows a schematic view of an embodiment of a portion of an in situ conversion system for treating a coal formation. Heat sources 44 may be placed within at least a portion of the coal formation. Heat sources 44 may include, for example, electric heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 44 may also include other types of heaters. Heat sources 44 may provide heat to at least a portion of a coal formation. In some

embodiments, heat may be provided to a first portion of a formation and transfer to a second portion of the formation (e.g., a pyrolysis zone). Energy may be supplied to the heat sources 44 through supply lines 46. Supply lines 46 may be structurally different depending on the type of heat source or heat sources being used to heat the formation. Supply lines 46 for heat sources 44 may transmit electricity for electric heaters, may transport fuel for combustors, or may transport heat exchange fluid that is circulated within the formation.

Production wells 48 may be used to remove formation fluid from the formation. Formation fluid produced from production wells 48 may be transported through collection piping 50 to treatment facilities 52. Formation fluids may also be produced from heat sources 44. For example, fluid may be produced from heat sources 44 to control pressure within the formation adjacent to the heat sources. Fluid produced from heat sources 44 may be transported through tubing or piping to collection piping 50 or the produced fluid may be transported through tubing or piping directly to treatment facilities 52. Treatment facilities 52 may include separation units, reaction units, upgrading units, fuel cells, turbines, storage vessels, and other systems and units for processing produced formation fluids.

An in situ conversion system for treating hydrocarbons may include barrier wells 54 (wells shown with reference number 54 may, in some embodiments, be dewatering wells, freeze wells, capture wells, isolation wells, and/or other types of barriers). In some embodiments, barrier wells 54 may be vacuum wells that remove liquid water and/or inhibit liquid water from entering a portion of a hydrocarbon containing formation to be heated, or to a formation being heated. A plurality of barrier wells 54 may surround all or a portion of a formation to be heated. In the embodiment depicted in FIG. 3, wells 54 are shown extending only along one side of heat sources 44, but barrier wells typically encircle all heat sources used, or to be used, to heat the formation.

In some embodiments, barrier wells 54 may be dewatering wells. In some embodiments, two or more rows of dewatering wells may surround a treatment area. In an embodiment, pressure differences between successive rows of dewatering wells may be minimized (e.g., maintained relatively low or near zero) to create a "no or low flow" boundary between rows.

In certain embodiments, wells initially used for one purpose may be later used for one or more other purposes, thereby lowering project costs and/or decreasing the time required to perform certain tasks. For instance, production wells (and in some circumstances heater wells) may initially be used as dewatering wells (e.g., before heating is begun and/or when heating is initially started). In addition, in some circumstances dewatering wells can later be used as production wells (and in some circumstances heater wells). As such, the dewatering wells may be placed and/or designed so that such wells can be later used as production wells and/or heater wells. The heater wells may be placed and/or designed so that such wells can be later used as production wells and/or dewatering wells. The production wells may be placed and/or designed so that such wells can be later used as dewatering wells and/or heater wells. Similarly, injection wells may be wells that initially were used for other purposes (e.g., heating, production, dewatering, monitoring, etc.), and injection wells may later be used for other purposes. Similarly, monitoring wells may be wells that initially were used for other purposes (e.g., heating, production, dewatering, injection, etc.), and monitoring wells may later be used for other purposes.

In some embodiments, heat sources will be placed within a heater well formed within a coal formation. The heater well may include an opening through an overburden of the formation. The heater may extend into or through at least one hydrocarbon layer of the formation. In a coal formation, the hydrocarbon layer is typically a coal layer. As shown in FIG. 4, an embodiment of heater well 56 may include an opening in hydrocarbon layer 58 that has a helical or spiral shape. A spiral heater well may increase contact with the formation as opposed to a

vertically positioned heater. A spiral heater well may provide expansion room that inhibits buckling or other modes of failure when the heater well is heated or cooled. In some embodiments, heater wells may include substantially straight sections through overburden 60. Use of a straight section of heater well through overburden 60 may decrease heat loss to the overburden and reduce the cost of heater well 56.

As shown in FIG. 5, a heat source embodiment may have a "U" shape. The legs of the "U" may be wider or more narrow depending on the particular heater well and formation characteristics. First portion 62 and third portion 64 of heater well 56 may be arranged substantially perpendicular to an upper surface of hydrocarbon layer 58 in some embodiments. In addition, the first and the third portion of the heater well may extend substantially vertically through overburden 60. Second portion 66 of heater well 56 may be substantially parallel to the upper surface of the hydrocarbon layer.

Multiple heat sources (e.g., 2, 3, 4, 5, 10 heat sources or more) may extend from a heater well in some situations. As shown in FIG. 6, heat sources 44, 44', and 44'' extend through overburden 60 into hydrocarbon layer 58 from heater well 56. Multiple wells extending from a single wellbore may be used when surface considerations (e.g., aesthetics, surface land use concerns, and/or unfavorable soil conditions near the surface) make it desirable to concentrate well platforms in a small area. For example, in areas where the soil is frozen and/or marshy, it may be more cost-effective to have a minimal number of well platforms located at selected sites.

In certain embodiments, a first portion of a heater well may extend from the ground surface, through an overburden, and into a coal formation. A second portion of the heater well may include one or more heater wells in the coal formation. The one or more heater wells may be disposed within the coal formation at various angles. In some embodiments, at least one of the heater wells may be disposed substantially parallel to a boundary of the coal formation. In alternate embodiments, at least one of the heater wells may be substantially perpendicular to the coal formation. In addition, one of the one or more heater wells may be positioned at an angle between perpendicular and parallel to a layer in the formation.

FIG. 7 depicts a schematic view from an elevated position of multiple heat sources branched from a single opening. In some embodiments, heat sources 44 may be used to generate heat along a length of the heater within vertical opening 68 and horizontal openings 70. In other embodiments, heat sources 44 may be used to generate heat only within horizontal openings 70. In certain embodiments, heat generated by heat sources 44 may be varied along its length and/or varied between vertical opening 68 and horizontal opening 70. For example, less heat may be generated by heat sources 44 in vertical opening 68 and more heat may be generated by the heater in horizontal opening 70. It may be advantageous to have at least some heating within vertical opening 68. This may maintain fluids produced from the formation in a vapor phase in production conduit 72 and/or may upgrade the produced fluids within the production well. Having production conduit 72 and heat sources 44 installed into a formation through a single opening in the formation may reduce costs associated with forming openings in the formation and installing production equipment and heaters within the formation.

One or more vertical openings 68 may be formed in hydrocarbon layer 58. Each of vertical openings 68 may lie along a single plane in hydrocarbon layer 58. Horizontal openings 70 may extend in a plane substantially perpendicular to the plane of vertical openings 68. In some embodiments, additional horizontal openings may lie in a plane below the depicted horizontal openings. A number of vertical openings 68 and/or a spacing between the vertical openings may be determined by, for example, a desired heating rate or a desired production rate. In some embodiments, spacing between vertical openings may be about 4 m to about 30 m. Longer or shorter spacings may be used to meet specific formation needs. A length of a horizontal opening 70 may be up to about 1600 m.

However, a length of horizontal openings 70 may vary depending on, for example, a maximum installation cost, an area of hydrocarbon layer 58, or a maximum producible heater length.

In an in situ conversion process embodiment, a formation having one or more thin hydrocarbon layers may be treated. In some in situ conversion process embodiments, such formations may be treated with heat sources that are positioned substantially horizontal within and/or adjacent to the thin hydrocarbon layer or thin hydrocarbon layers. A relatively thin hydrocarbon layer may be at a substantial depth below a ground surface. For example, a formation may have an overburden of up to about 650 m in depth. The cost of drilling a large number of substantially vertical wells within a formation to a significant depth may be expensive. It may be advantageous to place heaters horizontally within these formations to heat large portions of the formation for lengths up to about 1600 m. Using horizontal heaters may reduce the number of vertical wells that are needed to place a sufficient number of heaters within the formation.

An angle of hydrocarbon layer 58 relative to an upper surface of ground 74 may vary. For example, hydrocarbon layer 58 may dip or be steeply dipping relative to the upper surface of ground 74, as depicted in FIG. 8. In some embodiments, a hydrocarbon layer may be at a near-horizontal angle with respect to an upper surface of the ground. Economically viable production of a steeply dipping hydrocarbon containing layer may not be possible using presently available mining methods.

A dipping or relatively steeply dipping hydrocarbon layer 58 may be subjected to an in situ conversion process. A set of production wells 48 may be disposed near a highest portion of a dipping hydrocarbon layer 58 of a coal formation. A set of heater wells 56 may be placed in hydrocarbon layer 58. The set of heater wells 56 may be used to heat treatment area 76. Initially, a top portion of hydrocarbon layer 58 may be treated. Heat energy supplied by heater wells 56 may pyrolyze coal and produce hydrocarbon vapors that are produced from production wells 48. As production from the top portion declines, deeper portions of the formation may be heated to pyrolysis temperatures. Vapors produced in the hydrocarbon may move through the previously pyrolyzed coal. High permeability resulting from pyrolysis and production of fluid from the upper portion of the formation may allow for vapor phase transport with minimal pressure loss. Vapor phase transport of fluids produced in the formation may eliminate a need to have deep production wells in addition to the set of production wells. A number of production wells required to process the formation may be reduced. Reducing the number of production wells required for production may increase economic viability of the in situ conversion process.

Wellbores may be formed by directional drilling, geosteered drilling, drilling with a steerable motor and an accelerometer, impaction techniques and/or by sonic drilling techniques. The method used to form wellbores may be determined based on a number of factors. The factors may include, but are not limited to, accessibility of the site, depth of the wellbore, properties of the overburden, and properties of the hydrocarbon containing layer or layers.

FIG. 9 illustrates an embodiment of a plurality of heater wells 56 formed in hydrocarbon layer 58. Hydrocarbon layer 58 may be a steeply dipping layer. One or more of heater wells 56 may be formed in the formation such that two or more of the heater wells are substantially parallel to each other, and/or such that at least one heater well is substantially parallel to a boundary of hydrocarbon layer 58 with a non-hydrocarbon layer. For example, one or more of heater wells 56 may be formed in hydrocarbon layer 58 by a magnetic steering method. An example of a magnetic steering method is illustrated in U.S. Patent No. 5,676,212 to Kuckes. Magnetic steering may include drilling heater well 56 parallel to an adjacent heater well. The adjacent well may have been previously drilled. In addition, magnetic steering may include directing the drilling by sensing and/or determining a magnetic

field produced in an adjacent heater well. For example, the magnetic field may be produced in the adjacent heater well by flowing a current through an insulated current-carrying wireline disposed in the adjacent heater well.

In an in situ conversion process embodiment, a heating rate may be controlled to minimize costs associated with heating a selected section. The costs may include, for example, input energy costs and equipment costs. In certain embodiments, a cost associated with heating a selected section may be minimized by reducing a heating rate when the cost associated with heating is relatively high and increasing the heating rate when the cost associated with heating is relatively low. For example, a heating rate of about 330 watts/m may be used when the associated cost is relatively high, and a heating rate of about 1640 watts/m may be used when the associated cost is relatively low. In certain embodiments, heating rates may be varied between about 300 watts/m and about 800 watts/m when the associated cost is relatively high and between about 1000 watts/m and 1800 watts/m when the associated cost is relatively low. The cost associated with heating may be relatively high at peak times of energy use, such as during the daytime. For example, energy use may be high in warm climates during the daytime in the summer due to energy use for air conditioning. Low times of energy use may be, for example, at night or during weekends, when energy demand tends to be lower. In an embodiment, the heating rate may be varied from a higher heating rate during low energy usage times, such as during the night, to a lower heating rate during high energy usage times, such as during the day.

As shown in FIG. 3, in addition to heat sources 44, one or more production wells 48 will typically be placed within the portion of the coal formation. Formation fluids may be produced through production well 48. In some embodiments, production well 48 may include a heat source. The heat source may heat the portions of the formation at or near the production well and allow for vapor phase removal of formation fluids. The need for high temperature pumping of liquids from the production well may be reduced or eliminated. Avoiding or limiting high temperature pumping of liquids may significantly decrease production costs. Providing heating at or through the production well may: (1) inhibit condensation and/or refluxing of production fluid when such production fluid is moving in the production well proximate the overburden, (2) increase heat input into the formation, and/or (3) increase formation permeability at or proximate the production well. In some in situ conversion process embodiments, an amount of heat supplied to production wells is significantly less than an amount of heat applied to heat sources that heat the formation.

Embodiments of a production well may include valves that alter, maintain, and/or control a pressure of at least a portion of the formation. Production wells may be cased wells. Production wells may have production screens or perforated casings adjacent to production zones. In addition, the production wells may be surrounded by sand, gravel or other packing materials adjacent to production zones.

During an in situ process, production wells may be operated such that the production wells are at a lower pressure than other portions of the formation. In some embodiments, a vacuum may be drawn at the production wells. Maintaining the production wells at lower pressures may inhibit fluids in the formation from migrating outside of the in situ treatment area.

FIG. 10 illustrates a pattern of heat sources 44 and production wells 48 that may be used to treat a coal formation. Heat sources 44 may be arranged in a unit of heat sources such as triangular pattern 82. Heat sources 44, however, may be arranged in a variety of patterns including, but not limited to, squares, hexagons, and other polygons. The pattern may include a regular polygon to promote uniform heating of the formation in which the heat sources are placed. The pattern may also be a line drive pattern. A line drive pattern generally includes a first

linear array of heater wells, a second linear array of heater wells, and a production well or a linear array of production wells between the first and second linear array of heater wells.

Some in situ conversion process embodiments may be able to economically treat formations that were previously believed to be uneconomical to produce. Recovery of hydrocarbons from previously uneconomically producible formations may be possible because of the surprising increases in thermal conductivity and thermal diffusivity that can be achieved during thermal conversion of hydrocarbons within the formation by conductively and/or radiatively heating a portion of the formation. Surprising results are illustrated by the fact that prior literature indicated that certain coal formations, such as coal, exhibited relatively low values for thermal conductivity and thermal diffusivity when heated. For example, in government report No. 8364 by J. M. Singer and R. P. Tye entitled "Thermal, Mechanical, and Physical Properties of Selected Bituminous Coals and Cokes," U.S. Department of the Interior, Bureau of Mines (1979), the authors report the thermal conductivity and thermal diffusivity for four bituminous coals. This government report includes graphs of thermal conductivity and diffusivity that show relatively low values up to about 400 °C (e.g., thermal conductivity is about 0.2 W/(m °C) or below, and thermal diffusivity is below about  $1.7 \times 10^{-3} \text{ cm}^2/\text{s}$ ). This government report states: "coals and cokes are excellent thermal insulators."

In certain in situ conversion process embodiments, hydrocarbon containing resources (e.g., coal) may be treated such that the thermal conductivity and thermal diffusivity are significantly higher (e.g., thermal conductivity at or above about 0.5 W/(m °C) and thermal diffusivity at or above  $4.1 \times 10^{-3} \text{ cm}^2/\text{s}$ ) than would be expected based on previous literature, such as government report No. 8364. If a coal formation is subjected to an in situ conversion process, the coal does not act as "an excellent thermal insulator." Instead, heat can and does transfer and/or diffuse into the formation at significantly higher (and better) rates than would be expected according to the literature, thereby significantly enhancing economic viability of treating the formation.

In an in situ conversion process embodiment, heating a portion of a coal formation in situ to a temperature less than an upper pyrolysis temperature may increase permeability of the heated portion. Permeability may increase due to formation of thermal fractures within the heated portion. Thermal fractures may be generated by thermal expansion of the formation and/or by localized increases in pressure due to vaporization of liquids (e.g., water and/or hydrocarbons) in the formation. As a temperature of the heated portion increases, water in the formation may be vaporized. The vaporized water may escape and/or be removed from the formation. Removal of water may also increase the permeability of the heated portion. In addition, permeability of the heated portion may also increase as a result of mass loss from the formation due to generation of pyrolysis fluids in the formation. Pyrolysis fluid may be removed from the formation through production wells.

Heating the formation from heat sources placed in the formation may allow a permeability of the heated portion of a coal formation to be substantially uniform. A substantially uniform permeability may inhibit channeling of formation fluids in the formation and allow production from substantially all portions of the heated formation. An assessed (e.g., calculated or estimated) permeability of any selected portion in the formation having a substantially uniform permeability may not vary by more than a factor of 10 from an assessed average permeability of the selected portion.

Permeability of a selected section within the heated portion of the coal formation may rapidly increase when the selected section is heated by conduction. A permeability of an impermeable coal formation may be less than about 0.1 millidarcy ( $9.9 \times 10^{-17} \text{ m}^2$ ) before treatment. In some embodiments, pyrolyzing at least a portion of a coal formation may increase a permeability within a selected section of the portion to greater than about 10

millidarcy, 100 millidarcy, 1 darcy, 10 darcy, 20 darcy, or 50 darcy. A permeability of a selected section of the portion may increase by a factor of more than about 100, 1,000, 10,000, 100,000 or more.

In some in situ conversion process embodiments, superposition (e.g., overlapping influence) of heat from one or more heat sources may result in substantially uniform heating of a portion of a coal formation. Since formations during heating will typically have a temperature gradient that is highest near heat sources and reduces with increasing distance from the heat sources, "substantially uniform" heating means heating such that temperature in a majority of the section does not vary by more than 100 °C from an assessed average temperature in the majority of the selected section (volume) being treated.

Removal of hydrocarbons from the formation during an in situ conversion process may occur on a microscopic scale, as well as a macroscopic scale (e.g., through production wells). Hydrocarbons may be removed from micropores within a portion of the formation due to heating. Micropores may be generally defined as pores having a cross-sectional dimension of less than about 1000 Å. Removal of solid hydrocarbons may result in a substantially uniform increase in porosity within at least a selected section of the heated portion. Heating the portion of a coal formation may substantially uniformly increase a porosity of a selected section within the heated portion. "Substantially uniform porosity" means that the assessed (e.g., calculated or estimated) porosity of any selected portion in the formation does not vary by more than about 25% from the assessed average porosity of such selected portion.

Physical characteristics of a portion of a coal formation after pyrolysis may be similar to those of a porous bed. The physical characteristics of a formation subjected to an in situ conversion process may significantly differ from physical characteristics of a coal formation subjected to injection of gases that burn hydrocarbons to heat the hydrocarbons and or to formations subjected to steam flood production. Gases injected into virgin or fractured formations may channel through the formation. The gases may not be uniformly distributed throughout the formation. In contrast, a gas injected into a portion of a coal formation subjected to an in situ conversion process may readily and substantially uniformly contact the carbon and/or hydrocarbons remaining in the formation. Gases produced by heating the hydrocarbons may be transferred a significant distance within the heated portion of the formation with minimal pressure loss.

Transfer of gases in a formation over significant distances may be particularly advantageous to reduce the number of production wells needed to produce formation fluid from the formation. A first portion of a hydrocarbon containing formation may be subjected to an in situ conversion process. The volume of the formation subjected to in situ conversion may be expanded by heating abutting portions of the coal formation. Formation fluid produced in the abutting portions of the formation may be produced from production wells in the first portion. If needed, a few additional production wells may be installed in the abutting portions of formation, but such production wells may have large separation distances. The ability to transfer fluid in a formation over long distances may be advantageous for treating a steeply dipping coal formation. Production wells may be placed in an upper portion of the dipping hydrocarbon production. Heat sources may be inserted into the steeply dipping formation. The heat sources may follow the dip of the formation. The upper portion may be subjected to thermal treatment by activating portions of the heat sources in the upper portion. Abutting portions of the steeply dipping formation may be subjected to thermal treatment after treatment in the upper portion increases the permeability of the formation so that fluids in lower portions may be produced from the upper portions.

In an embodiment, production of hydrocarbons from a formation is inhibited until at least some hydrocarbons within the formation have been pyrolyzed. A mixture may be produced from the formation at a time



when the mixture includes a selected quality in the mixture (e.g., API gravity, hydrogen concentration, aromatic content, etc.). In some embodiments, the selected quality includes an API gravity of at least about 20°, 30°, or 40°. Inhibiting production until at least some hydrocarbons are pyrolyzed may increase conversion of heavy hydrocarbons to light hydrocarbons. Inhibiting initial production may minimize the production of heavy hydrocarbons from the formation. Production of substantial amounts of heavy hydrocarbons may require expensive equipment and/or reduce the life of production equipment.

When production of hydrocarbons from the formation is inhibited, the pressure in the formation tends to increase with temperature in the formation because of thermal expansion and/or phase change of heavy hydrocarbons and other fluids (e.g., water) in the formation. Pressure within the formation may have to be maintained below a selected pressure to inhibit unwanted production, fracturing of the overburden or underburden, and/or coking of hydrocarbons in the formation. The selected pressure may be a lithostatic or hydrostatic pressure of the formation. For example, the selected pressure may be about 150 bars absolute or, in some embodiments, the selected pressure may be about 35 bars absolute. The pressure in the formation may be controlled by controlling production rate from production wells in the formation. In other embodiments, the pressure in the formation is controlled by releasing pressure through one or more pressure relief wells in the formation. Pressure relief wells may be heat sources or separate wells inserted into the formation. Formation fluid removed from the formation through the relief wells may be sent to a surface facility. Producing at least some hydrocarbons from the formation may inhibit the pressure in the formation from rising above the selected pressure.

A slow heating process may produce condensed hydrocarbon fluids having API gravities in a range of 22° to 50°, and average molecular weights of about 150 g/gmol to about 250 g/gmol.

In some embodiments, migration of fluids into and/or out of a treatment area in a formation may be inhibited by the use of barriers. Barriers may include, but are not limited to naturally occurring portions (e.g., overburden and/or underburden), frozen barrier zones, low temperature barrier zones, grout walls, sulfur wells, dewatering wells, injection wells, a barrier formed by a gel produced in the formation, a barrier formed by precipitation of salts in the formation, a barrier formed by a polymerization reaction in the formation, sheets driven into the formation, and/or combinations thereof. Barriers may define the treatment area. Alternatively, barriers may be provided to a portion of the treatment area.

FIG. 11 depicts an embodiment of treatment areas 76 surrounded by perimeter barrier 84. Perimeter barrier 84 may define a limited volume of formation that is to be treated by an in situ conversion process. The limited volume of formation is known as treatment area 76. Defining a limited volume of formation that is to be treated may allow operating conditions within the limited volume to be more readily controlled.

Perimeter barrier 84 may include installed portions and naturally occurring portions of the formation. Naturally occurring portions of the formation that form part of a perimeter barrier may include substantially impermeable layers of the formation. Examples of naturally occurring perimeter barriers include overburdens and underburdens. Installed portions of perimeter barrier 84 may be formed as needed to define separate treatment areas 76. In situ conversion process (ICP) wells 86 may be placed within treatment areas 76. ICP wells 86 may include heat sources, production wells, treatment area dewatering wells, monitor wells, and other types of wells used during in situ conversion.

Different treatment areas 76 may share common barrier sections to minimize the length of perimeter barrier 84 that needs to be formed. Perimeter barrier 84 may inhibit fluid migration into treatment area 76 undergoing in situ conversion. Advantageously, perimeter barrier 84 may inhibit formation water from migrating

into treatment area 76. Formation water typically includes water and dissolved material in the water (e.g., salts). If formation water were allowed to migrate into treatment area 76 during an in situ conversion process, the formation water might increase operating costs for the process by adding additional energy costs associated with vaporizing the formation water and additional fluid treatment costs associated with removing, separating, and treating additional water in formation fluid produced from the formation. A large amount of formation water migrating into a treatment area may inhibit heat sources from raising temperatures within portions of treatment area 76 to desired temperatures.

Certain types of perimeter barriers 84 (e.g., frozen barriers) between adjacent treatment areas 76 may allow adjacent treatment areas to undergo different in situ conversion processes. For example, a first treatment area may be undergoing pyrolysis, a second treatment area adjacent to the first treatment area may be undergoing synthesis gas generation, and a third treatment area adjacent to the first treatment area and/or the second treatment area may be subjected to an in situ mining process. Operating conditions within the different treatment areas may be at different temperatures, pressures, production rates, heat injection rates, etc.

In some formations, a hydrocarbon containing layer that is to be subjected to in situ conversion is located in a portion of the formation that is permeable and/or fractured. Without perimeter barrier 84, formation fluid produced during in situ conversion might migrate out of the volume of formation being treated. Flow of formation fluid out of the volume of formation being treated may inhibit the ability to maintain a desired pressure within the portion of the formation being treated. Thus, defining a limited volume of formation that is to be treated by using perimeter barrier 84 may allow the pressure within the limited volume to be controlled. Controlling the amount of fluid removed from treatment area 76 through pressure relief wells, production wells and/or heat sources may allow pressure within the treatment area to be controlled. In some embodiments, pressure relief wells are perforated casings placed within or adjacent to wellbores of heat sources that have sealed casings, such as flameless distributed combustors. The use of some types of perimeter barriers (e.g., frozen barriers and grout walls) may allow pressure control in individual treatment areas 76.

During in situ conversion, heat applied to the formation may cause fractures to develop within treatment area 76. Some of the fractures may propagate towards a perimeter of treatment area 76. A propagating fracture may intersect an aquifer and allow formation water to enter treatment area 76. Formation water entering treatment area 76 may not permit heat sources in a portion of the treatment area to raise the temperature of the formation to temperatures significantly above the vaporization temperature of formation water entering the formation. Fractures may also allow formation fluid produced during in situ conversion to migrate away from treatment area 76.

Perimeter barrier 84 around treatment area 76 may limit the effect of a propagating fracture on an in situ conversion process. In some embodiments, perimeter barriers 84 are located far enough away from treatment areas 76 so that fractures that develop in the formation do not influence perimeter barrier integrity. Perimeter barriers 84 may be located over 10 m, 40 m, or 70 m away from ICP wells 86. In some embodiments, perimeter barrier 84 may be located adjacent to treatment area 76. For example, a frozen barrier formed by freeze wells may be located close to heat sources, production wells, or other wells. ICP wells 86 may be located less than 1 m away from freeze wells, although a larger spacing may advantageously limit influence of the frozen barrier on the ICP wells, and limit the influence of formation heating on the frozen barrier.

Perimeter barriers may be useful to address regulatory issues and/or to insure that areas proximate a treatment area (e.g., water tables or other environmentally sensitive areas) are not substantially affected by an in situ conversion process. The formation within the perimeter barrier may be treated using an in situ conversion process.

The perimeter barrier may inhibit the formation on an outer side of the perimeter barrier from being affected by the in situ conversion process used on the formation within the perimeter barrier. Perimeter barriers may inhibit fluid migration from a treatment area. Perimeter barriers may inhibit rise in temperature to pyrolysis temperatures on outer sides of the perimeter barriers.

5 Some formations may have relatively thin overburdens over a portion of the formation. Some formations may have an outcrop that approaches or extends to ground surface. In some formations, an overburden may have fractures or develop fractures during thermal processing that connect or approach the ground surface. Some formations may have permeable portions that allow formation fluid to escape to the atmosphere when the formation is heated. A ground cover may be provided for a portion of a formation that will allow, or potentially allow,  
10 formation fluid to escape to the atmosphere during thermal processing.

In situ treatment of formations may significantly alter formation characteristics such as permeability and structural strength. Production of hydrocarbons from a formation corresponds to removal of hydrocarbon containing material from the formation. Heat added to the formation may, in some embodiments, fracture the formation. Removal of hydrocarbon containing material and formation of fractures may influence the structural  
15 integrity of the formation. Selected areas of a treatment area may remain untreated to promote structural integrity of the formation, to inhibit subsidence, and/or to inhibit fracture propagation.

Hydrocarbon fluids were produced from a portion of a coal formation by an in situ experiment conducted in a portion of a coal formation. The coal was high volatile bituminous C coal. The formation was heated with electric heaters. FIG. 12 depicts a cross-sectional representation of the in situ experimental field test system. As  
20 shown in FIG. 12, the experimental field test system included coal formation 88. Treatment area 76 was within perimeter barrier 84. Perimeter barrier 84 was a grout wall. Hydrocarbon layer 58 dipped at an angle of approximately 36° with a thickness of approximately 4.9 m. FIG. 13 illustrates a location of heat sources 44a, 44b, 44c, production wells 48a, 48b, and observation wells 90a, 90b, 90c, 90d used for the experimental field test system. The three heat sources were disposed in a triangular configuration. Production well 48a was located  
25 proximate a center of the heat source pattern and equidistant from each of the heat sources. Second production well 48b was located outside the heat source pattern and spaced equidistant from the two closest heat sources. Perimeter barrier 84 was formed around the heat source pattern and the production wells. The grout wall was formed of 24 pillars. Perimeter barrier 84 inhibited an influx of water into the portion during the in situ experiment. In addition, perimeter barrier 84 inhibited loss of generated hydrocarbon fluids to an unheated portion of the formation.

30 Temperatures were measured at various times during the experiment at each of four observation wells 90a, 90b, 90c, 90d located within and outside of the heat source pattern as shown in FIG. 13. The temperatures measured at each of the observation wells are displayed in FIG. 14 as a function of time. Temperatures at observation wells 90a (represented by line 92a), 90b (represented by line 92b), and 90c (represented by line 92c) were relatively close to each other. A temperature at temperature observation well 90d (92d) was significantly  
35 colder. This temperature observation well was located outside of the heater well triangle illustrated in FIG. 13. This data demonstrates that in zones where there was little superposition of heat, temperatures were significantly lower. FIG. 15 illustrates temperature profiles measured at heat sources 44a (represented by line 94a), 44b (represented by line 94b), and 44c (represented by line 94c). The temperature profiles were relatively uniform at the heat sources.

40 FIG. 16 illustrates a plot of cumulative volume (m<sup>3</sup>) of liquid hydrocarbons produced 96 as a function of time (days). FIG. 17 illustrates a plot of cumulative volume of gas produced 98 in standard cubic feet, produced as

a function of time (in days) for the same in situ experiment. Both FIG. 16 and FIG. 17 show the results during the pyrolysis stage only of the in situ experiment.

FIG. 18 illustrates the carbon number distribution of condensable hydrocarbons that were produced using a slow, low temperature retorting process. Relatively high quality products were produced during treatment. The results in FIG. 18 are consistent with the results set forth in FIG. 19, which show results from heating coal from the same formation in the laboratory for similar ranges of heating rates as were used in situ.

TABLE 1 tabulates analysis results of coal before and after being subjected to thermal treatment (including heating pyrolysis and production of synthesis gas). The coal was cored from formation about 11-11.3 m below the surface and midway into the coal bed, in both the "before treatment" and "after treatment" samples. Both cores were taken at about the same location. Both cores were taken about 0.66 m from heater source 44c (between perimeter barrier 84 and heater source 44c) shown in FIG. 13. In the following TABLE 1 "FA" is the Fischer Assay, "as rec'd" means the sample was tested as it was received and without any further treatment, "Py-Water" is the water produced during pyrolysis, "H/C Atomic Ratio" is the atomic ratio of hydrogen to carbon, "daf" means "dry ash free," "dmmf" means "dry mineral matter free," and "mmf" means "mineral matter free." The specific gravity of the "after treatment" core sample was approximately 0.85 whereas the specific gravity of the "before treatment" core sample was approximately 1.35.

TABLE 1

<u>Analysis</u>	<u>Before Treatment</u>	<u>After Treatment</u>
% Vitrinite Reflectance	0.54	5.16
FA (gal/ton, as-rec'd)	11.81	0.17
FA (wt%, as rec'd)	6.10	0.61
FA Py-Water (gal/ton, as-rec'd)	10.54	2.22
H/C Atomic Ratio	0.85	0.06
H (wt%, daf)	5.31	0.44
O (wt%, daf)	17.08	3.06
N (wt%, daf)	1.43	1.35
Ash (wt%, as rec'd)	32.72	56.50
Fixed Carbon (wt%, dmmf)	54.45	94.43
Volatile Matter (wt%, dmmf)	45.55	5.57
Heating Value (Btu/lb, moist, mmf)	12048	14281

Even though the cores were taken outside the areas within the triangle formed by the three heaters in FIG. 13, the cores demonstrate that the coal remaining in the formation changed significantly during treatment. The vitrinite reflectance results shown in TABLE 1 demonstrate that the rank of the coal remaining in the formation increased substantially during treatment. The coal was a high volatile bituminous C coal before treatment. After treatment, however, the coal was essentially anthracite. In an embodiment, produced coal may have a vitrinite reflectance greater than about 2.9% and/or a heating value greater than about 25,000kJ/kg.

The Fischer Assay results shown in TABLE 1 demonstrate that most of the hydrocarbons in the coal had been removed during treatment. The H/C Atomic Ratio demonstrates that most of the hydrogen in the coal had been removed during treatment. A significant amount of nitrogen and ash was left in the formation.

In sum, the results shown in TABLE 1 demonstrate that a significant amount of hydrocarbons and hydrogen were removed during treatment of the coal by pyrolysis and generation of synthesis gas. Significant amounts of undesirable products (ash and nitrogen) remain in the formation, while significant amounts of desirable products (e.g., condensable hydrocarbons and gas) were removed.

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.

## WHAT IS CLAIMED IS:

1. A method of producing upgraded coal from a coal formation, comprising:  
producing upgraded coal from at least a portion of a treated formation, wherein the formation is treated  
5 by:  
providing heat from one or more heaters to at least a portion of the formation;  
allowing the heat to transfer from at least one or more heaters to a part of the formation;  
producing fluids from the formation; and  
wherein the treatment upgrades at least a part of the coal.  
10
2. The method of claim 1, wherein the formation is at least partially pyrolyzed.
3. The method of claim 1 or 2, wherein at least some hydrocarbons in the coal have been pyrolyzed.
- 15 4. The method of any one of claims 1-3, wherein producing the coal comprises producing the coal as a powder.
5. The method of any one of claims 1-3, wherein producing the coal comprises producing the coal as a  
slurry.  
20
6. The method of any one of claims 1-5, further comprising providing a fluid to the portion to remove at  
least some coal.
7. The method of any one of claims 1-6, wherein the produced coal comprises anthracite.  
25
8. The method of any one of claims 1-6, wherein the coal, before treatment, did not comprise a substantial  
quantity of anthracite, and the produced coal comprises a substantial quantity of anthracite.
9. The method of any one of claims 1-8, wherein at least some of the produced coal comprises a carbon  
30 content of greater than about 87 weight %.
10. The method of any one of claims 1-9, wherein at least some of the produced coal comprises a volatile  
matter content of less than about 5 weight %.
- 35 11. The method of any one of claims 1-10, wherein at least some of the produced coal comprises a heating  
value greater than about 25,000 kJ/kg.

12. The method of any one of claims 1-11, wherein at least some of the produced coal comprises a vitrinite reflectance of greater than about 2.9 %.

13. The method of any one of claims 1-12, wherein at least a portion of the produced coal is used in the  
5 production of steel.

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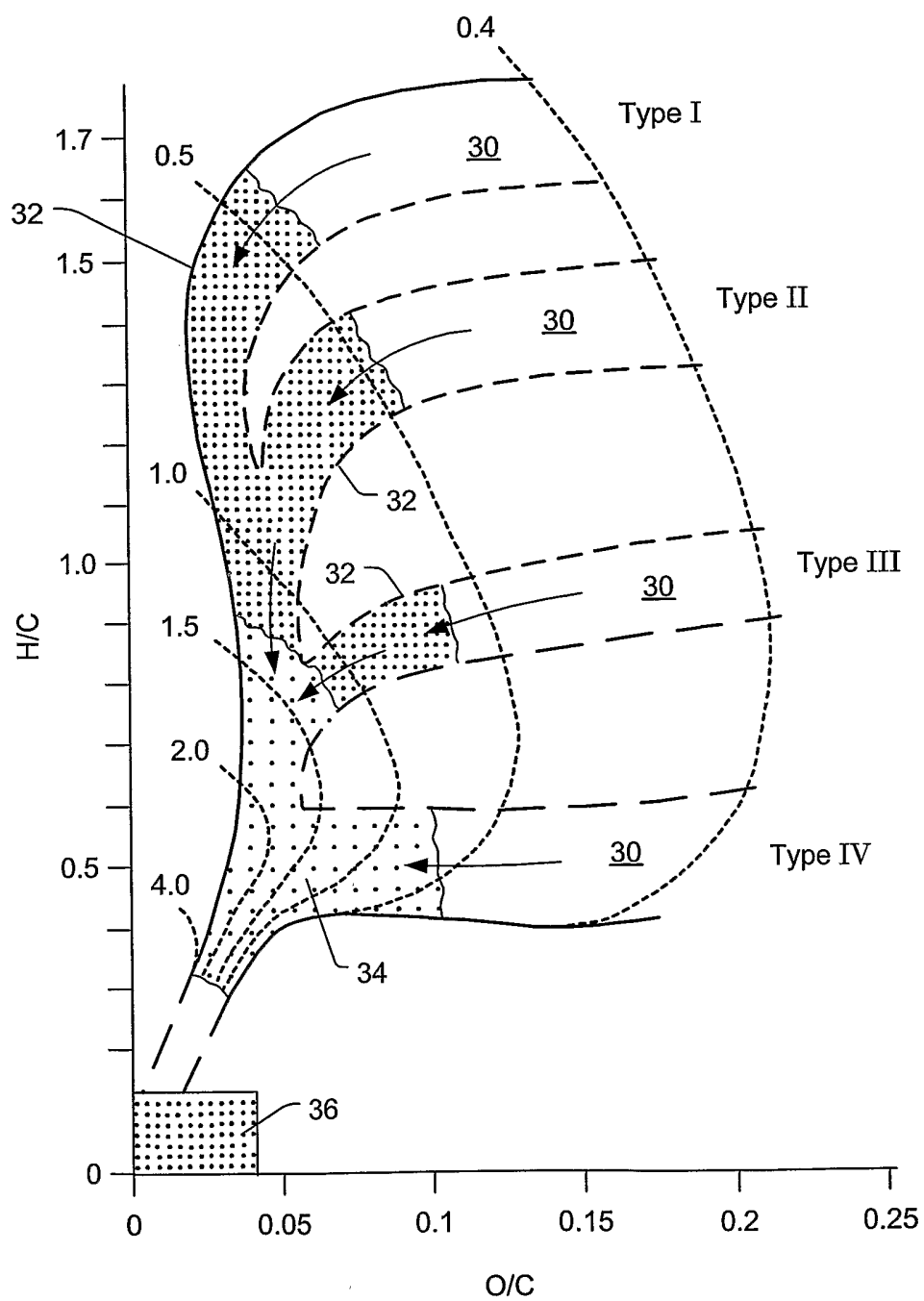


FIG. 1



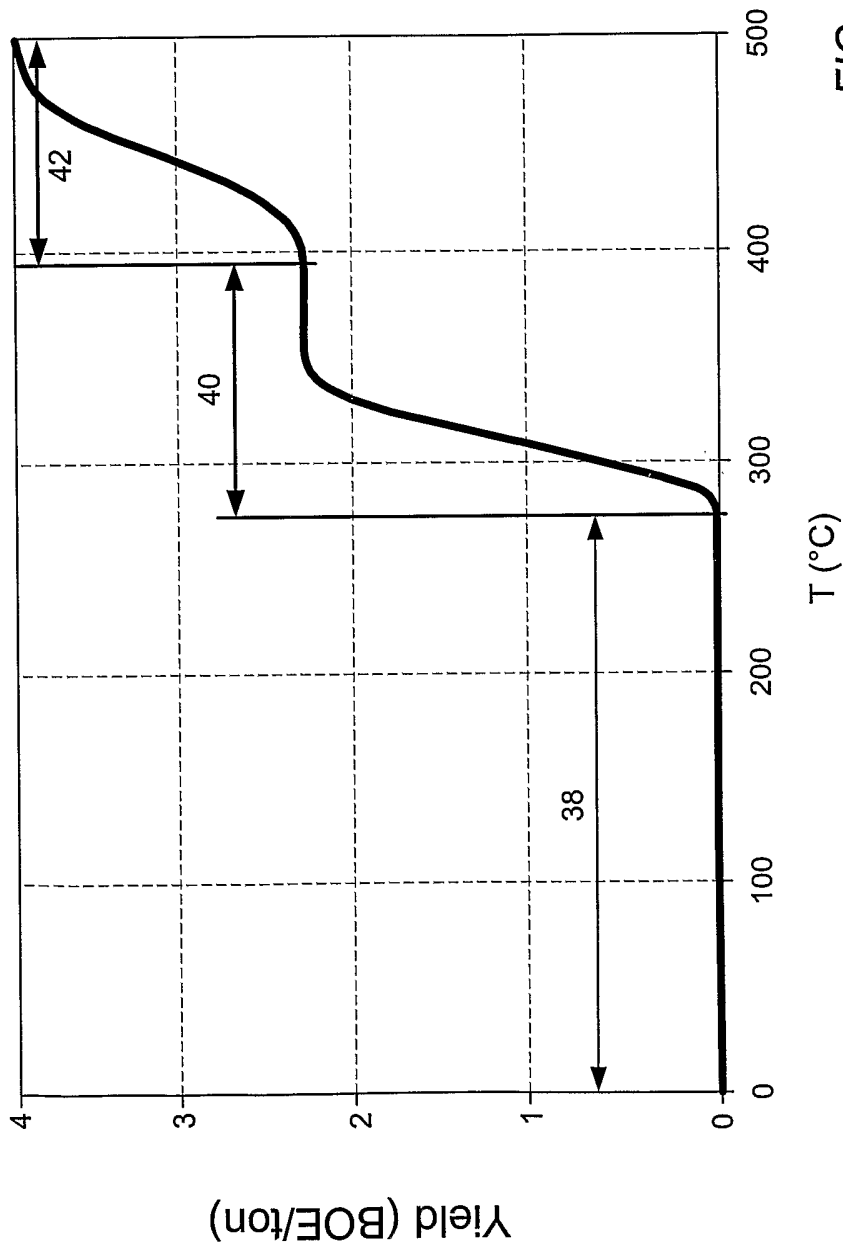
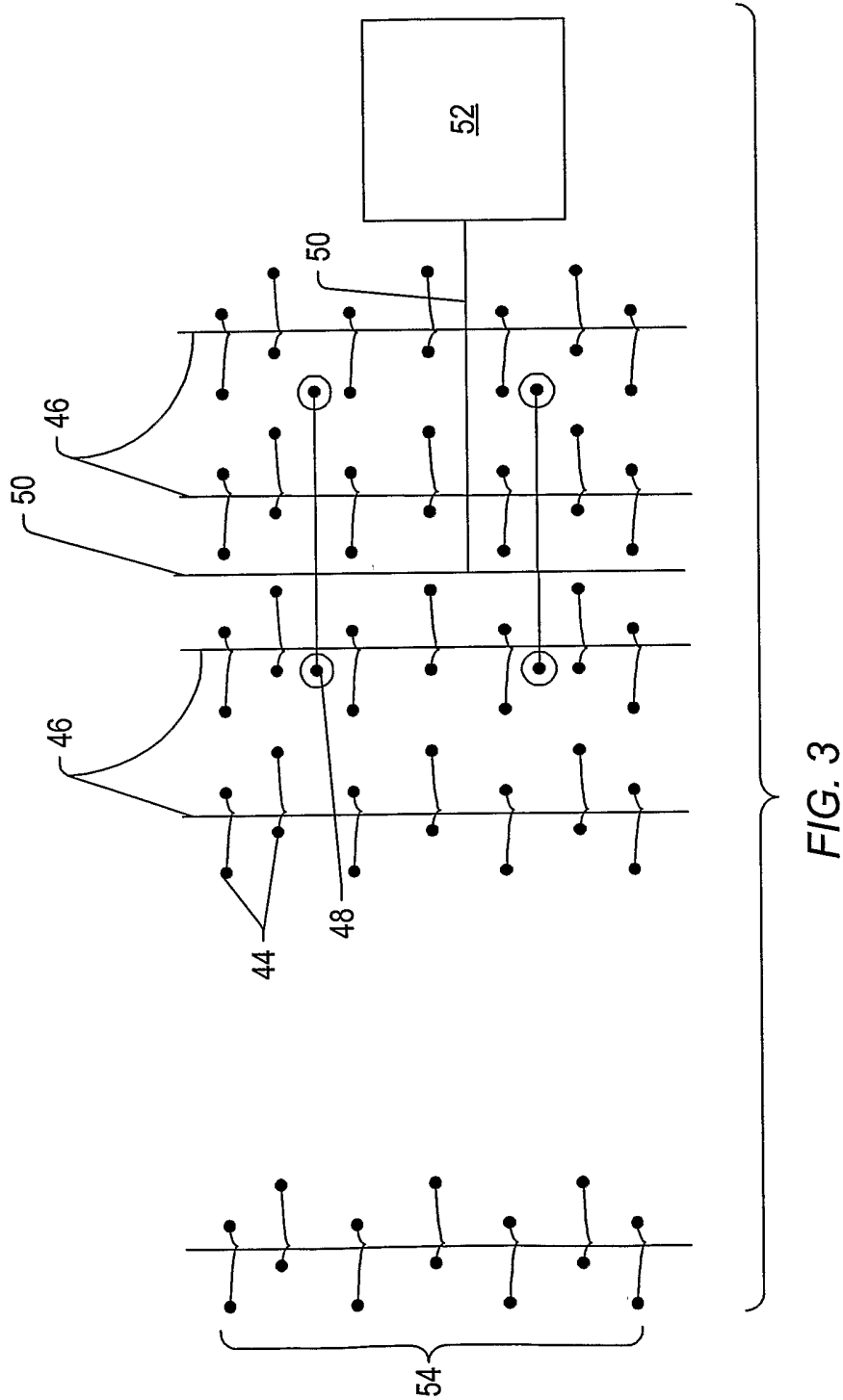


FIG. 2



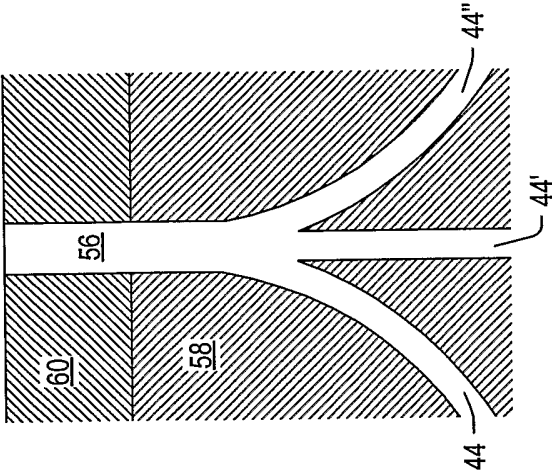


FIG. 6

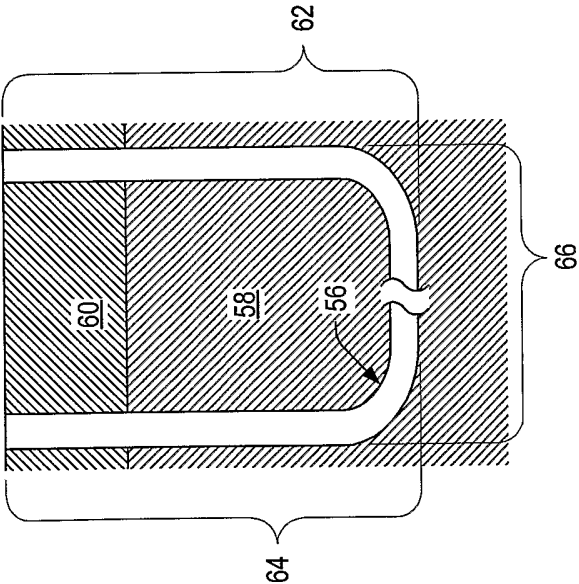


FIG. 5

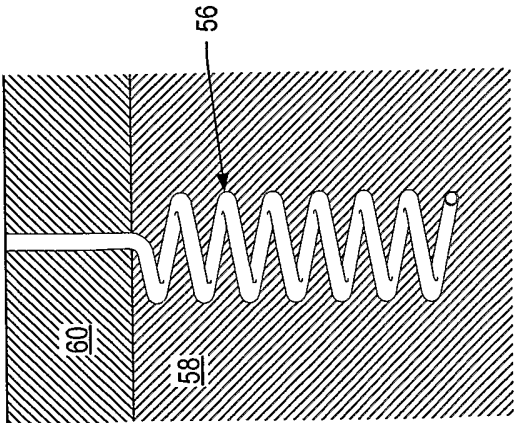


FIG. 4

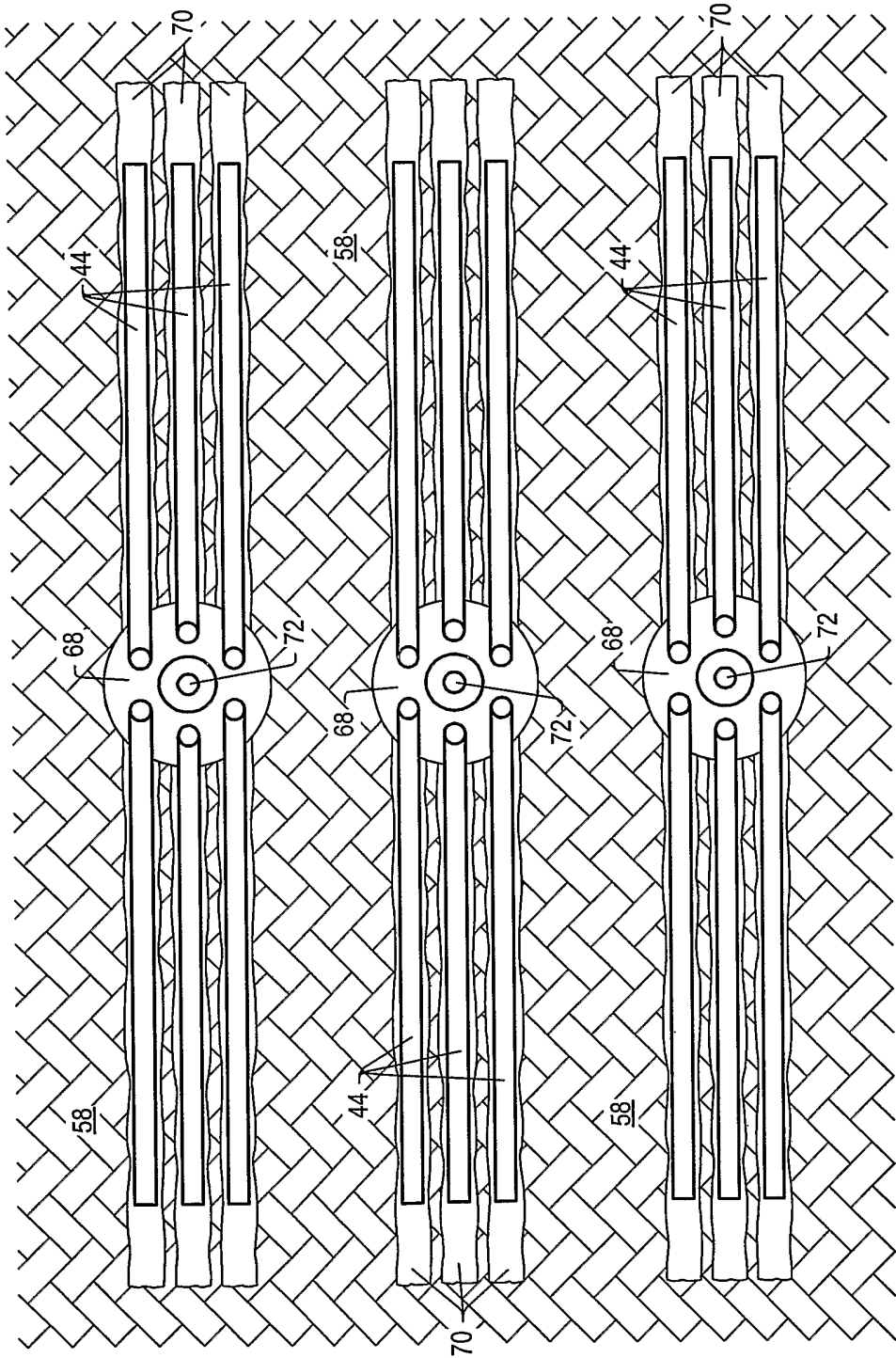
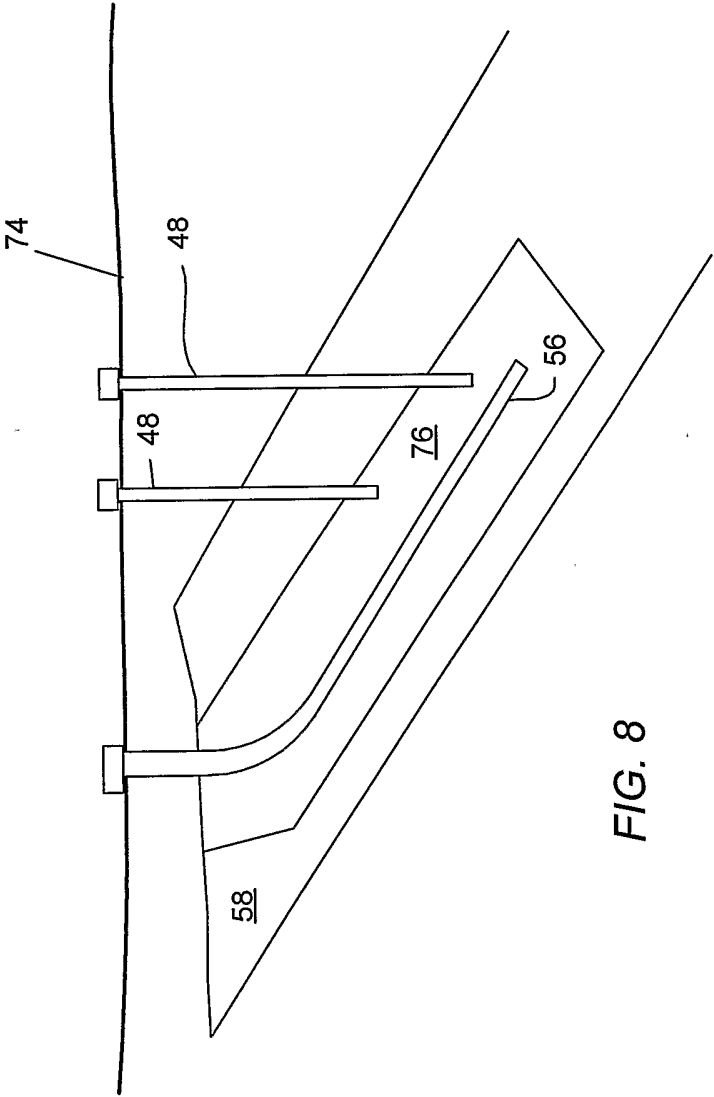


FIG. 7



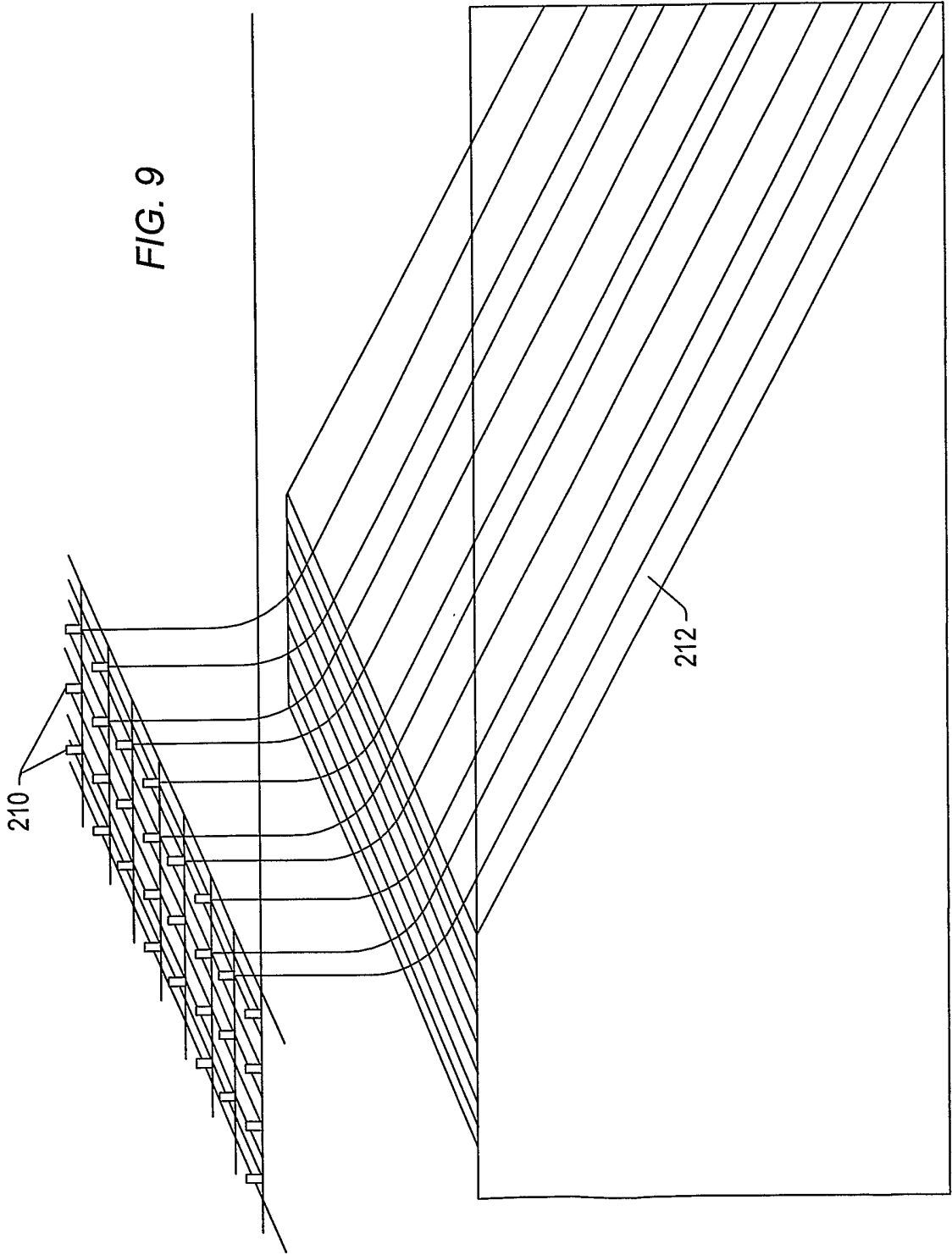
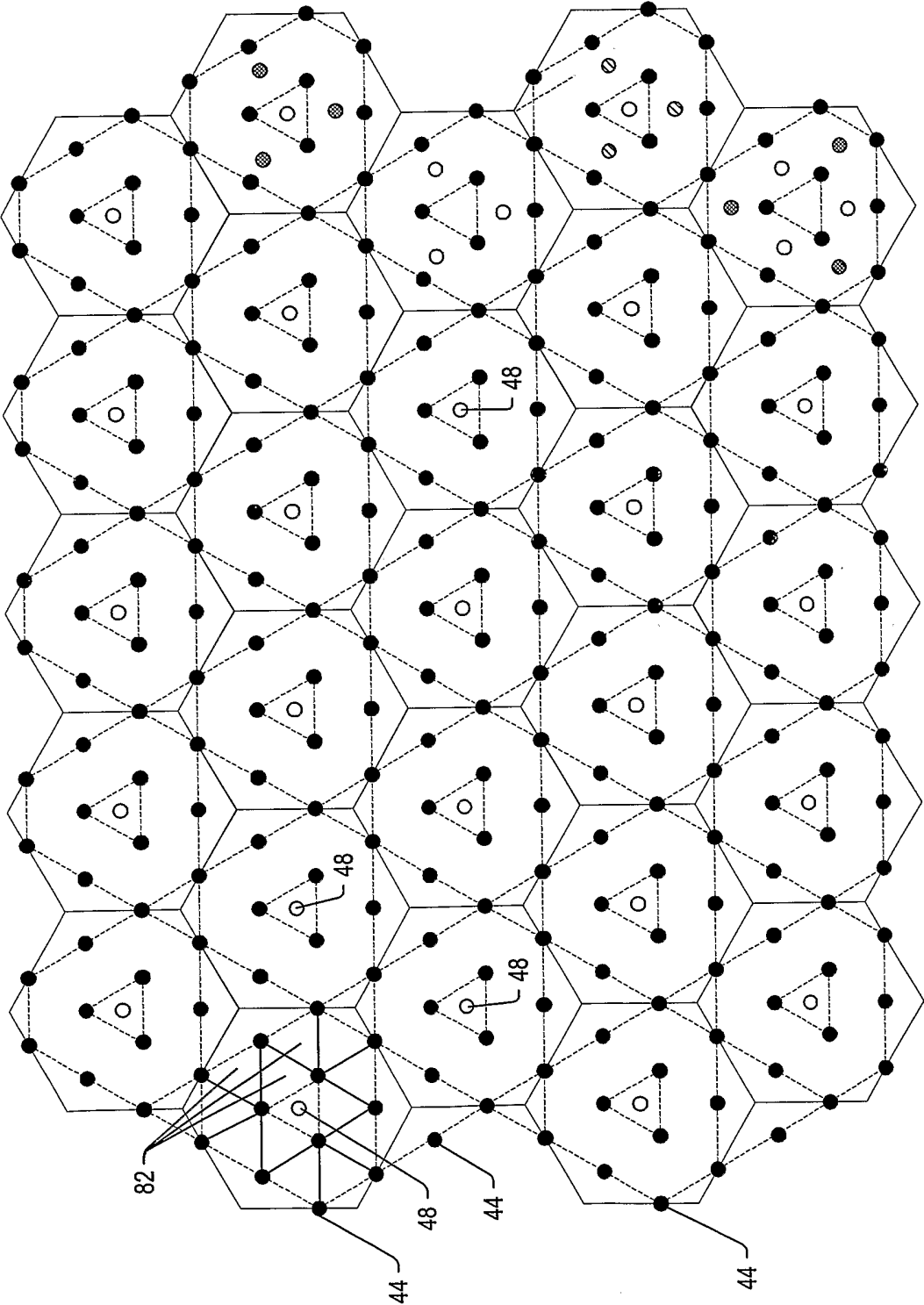


FIG. 10



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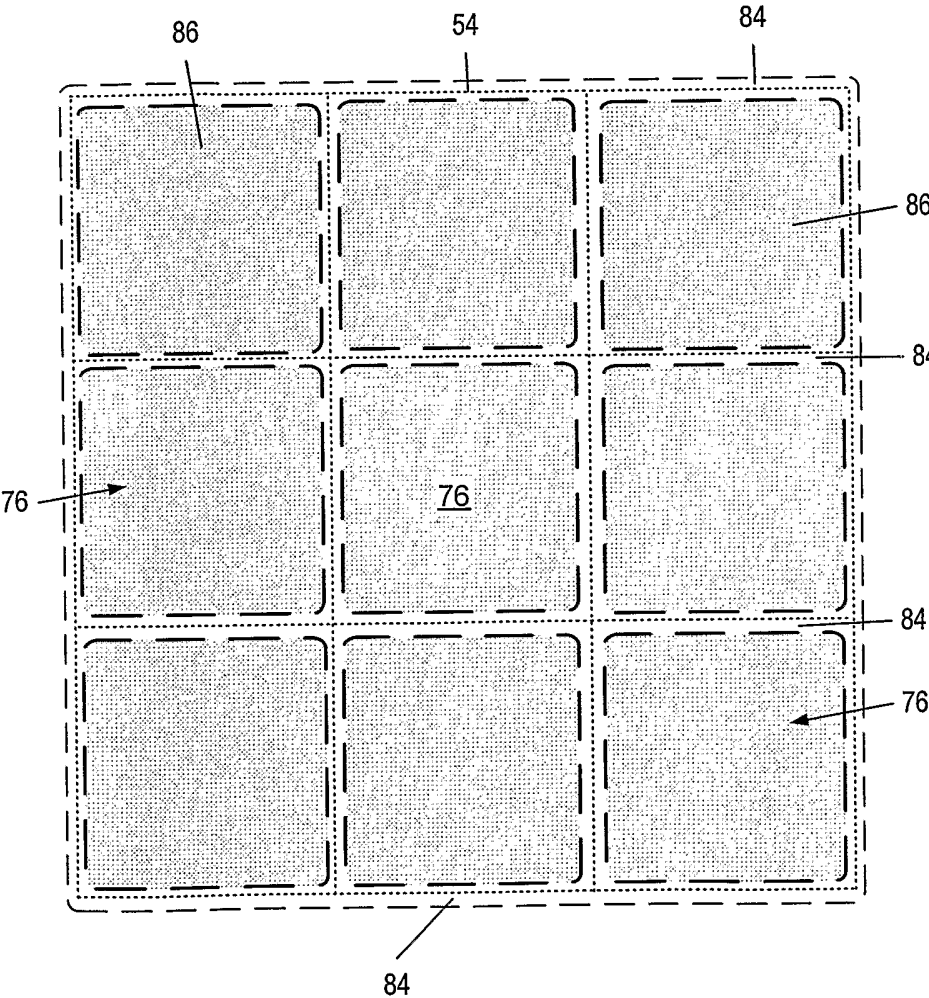


FIG. 11



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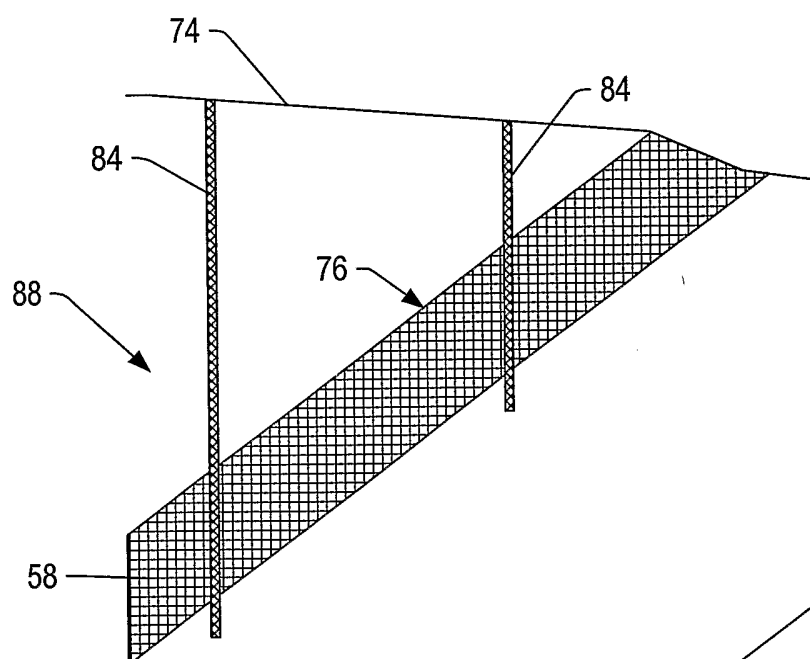


FIG. 12

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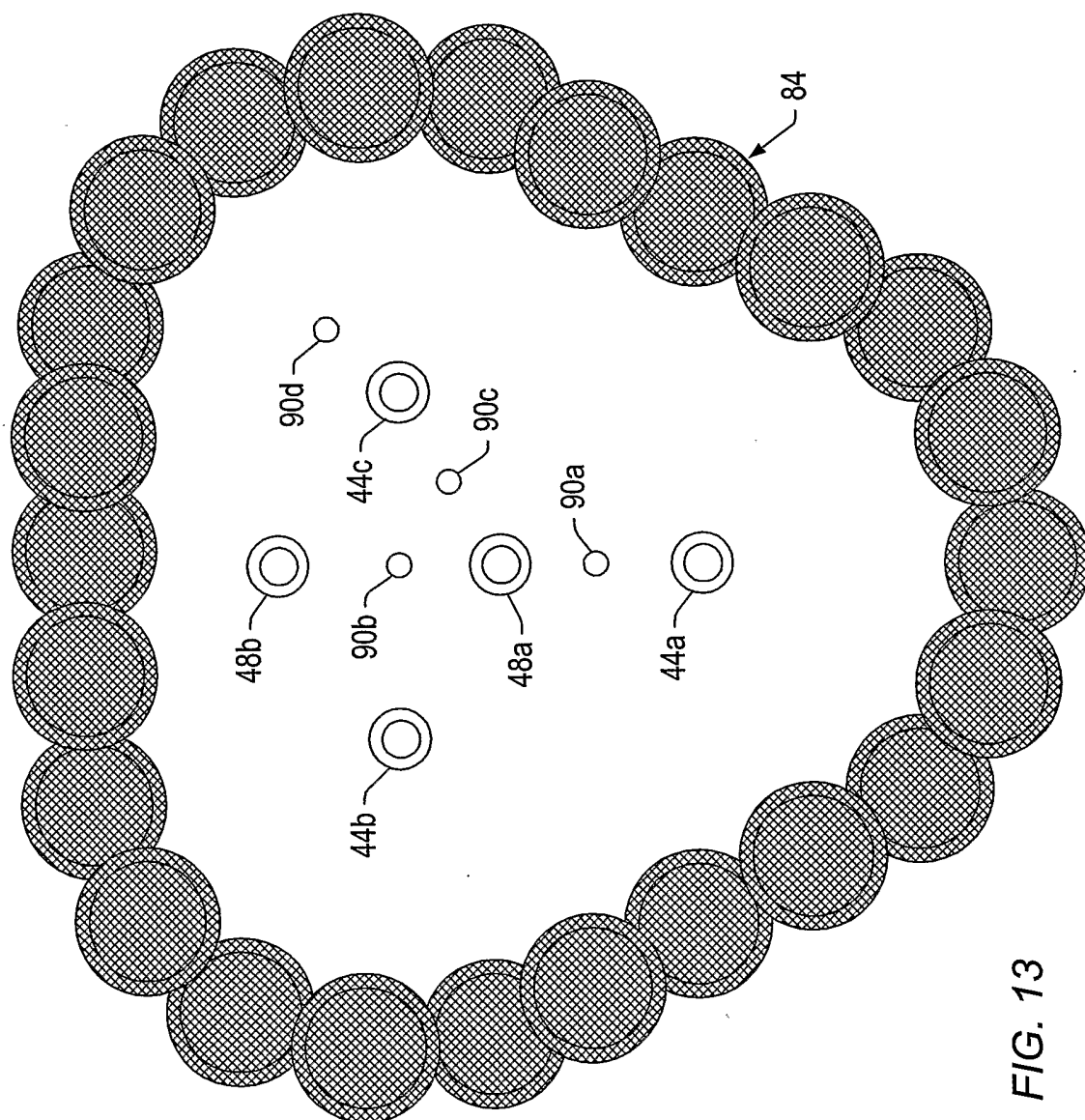
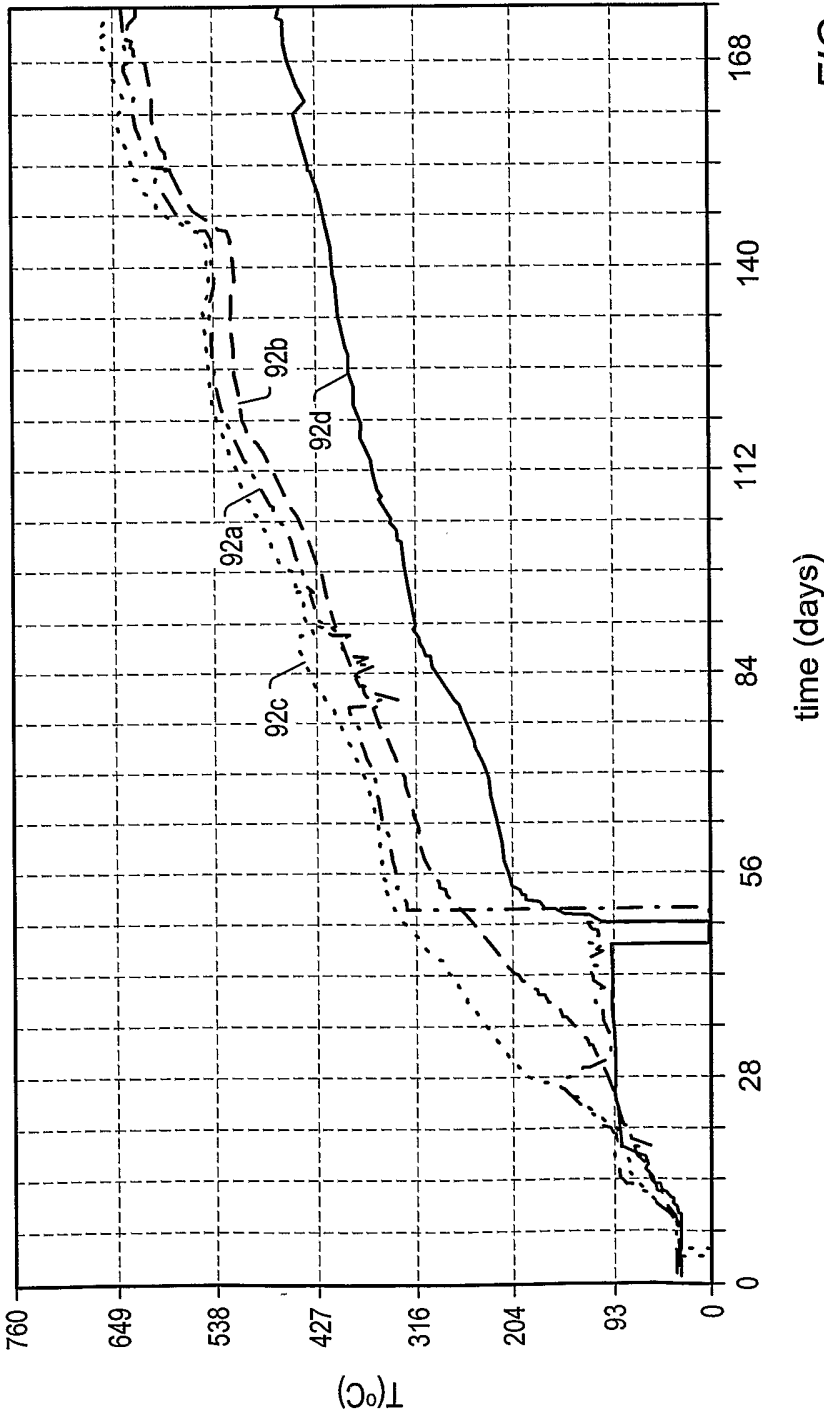


FIG. 13

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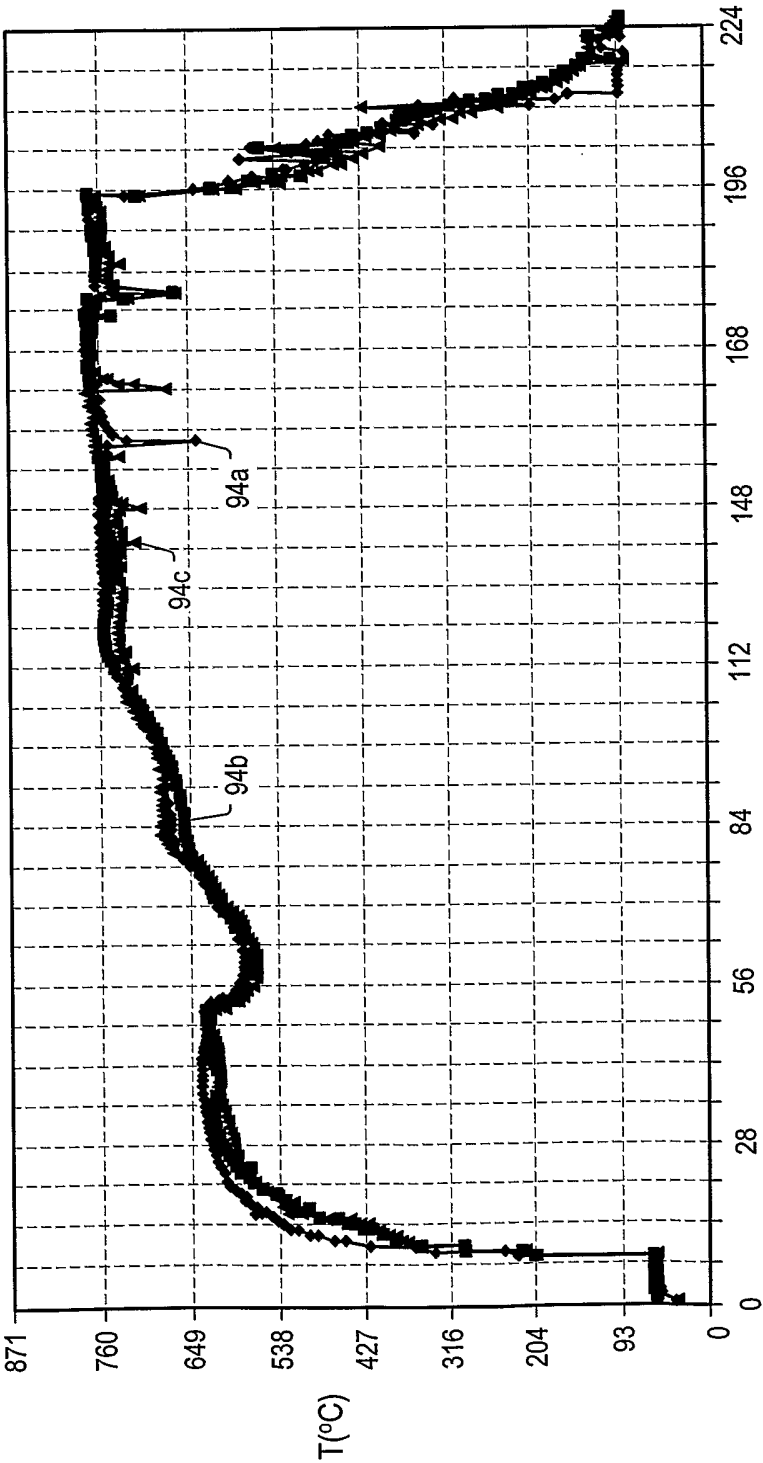


FIG. 15

time (days)

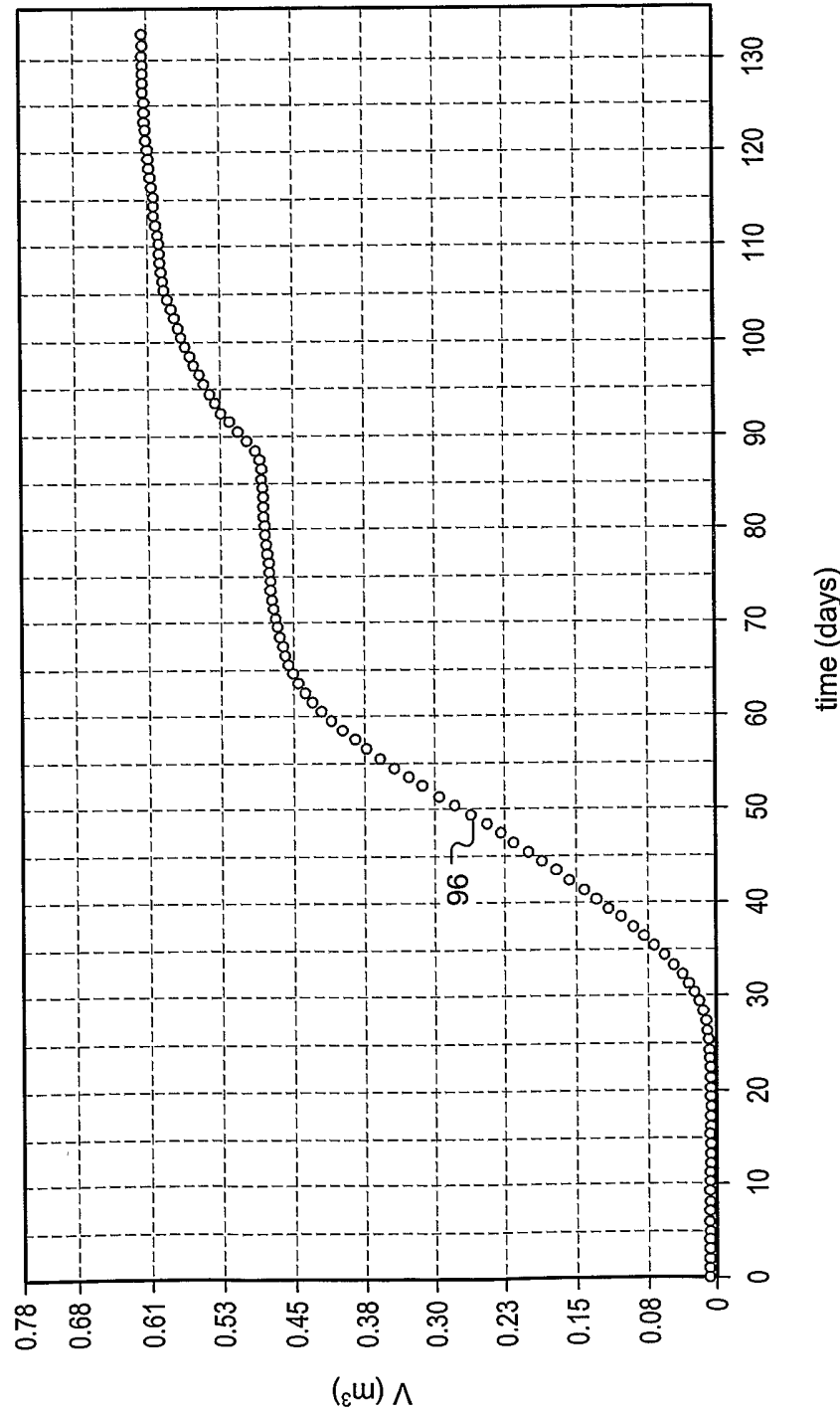


FIG. 16

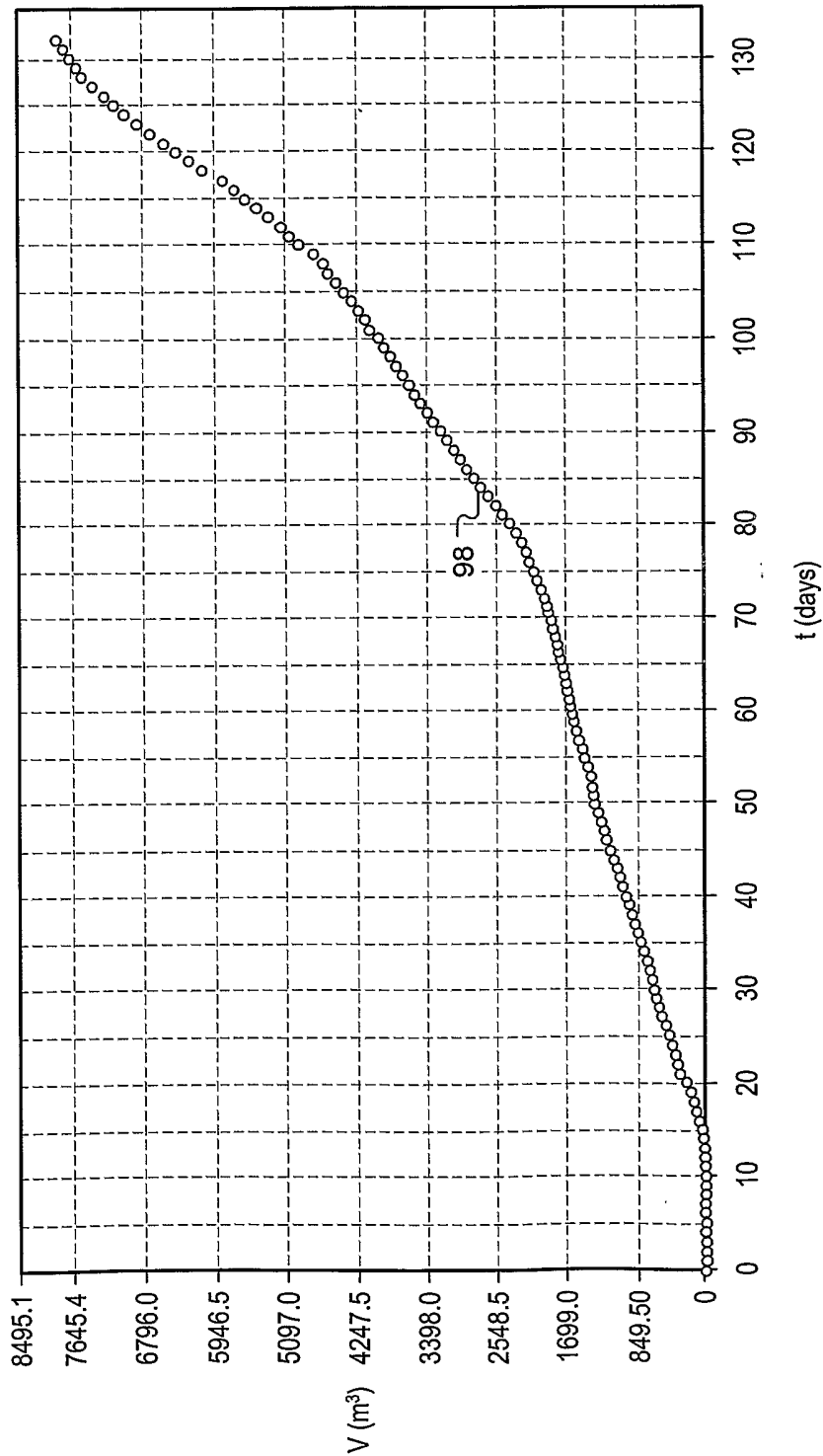
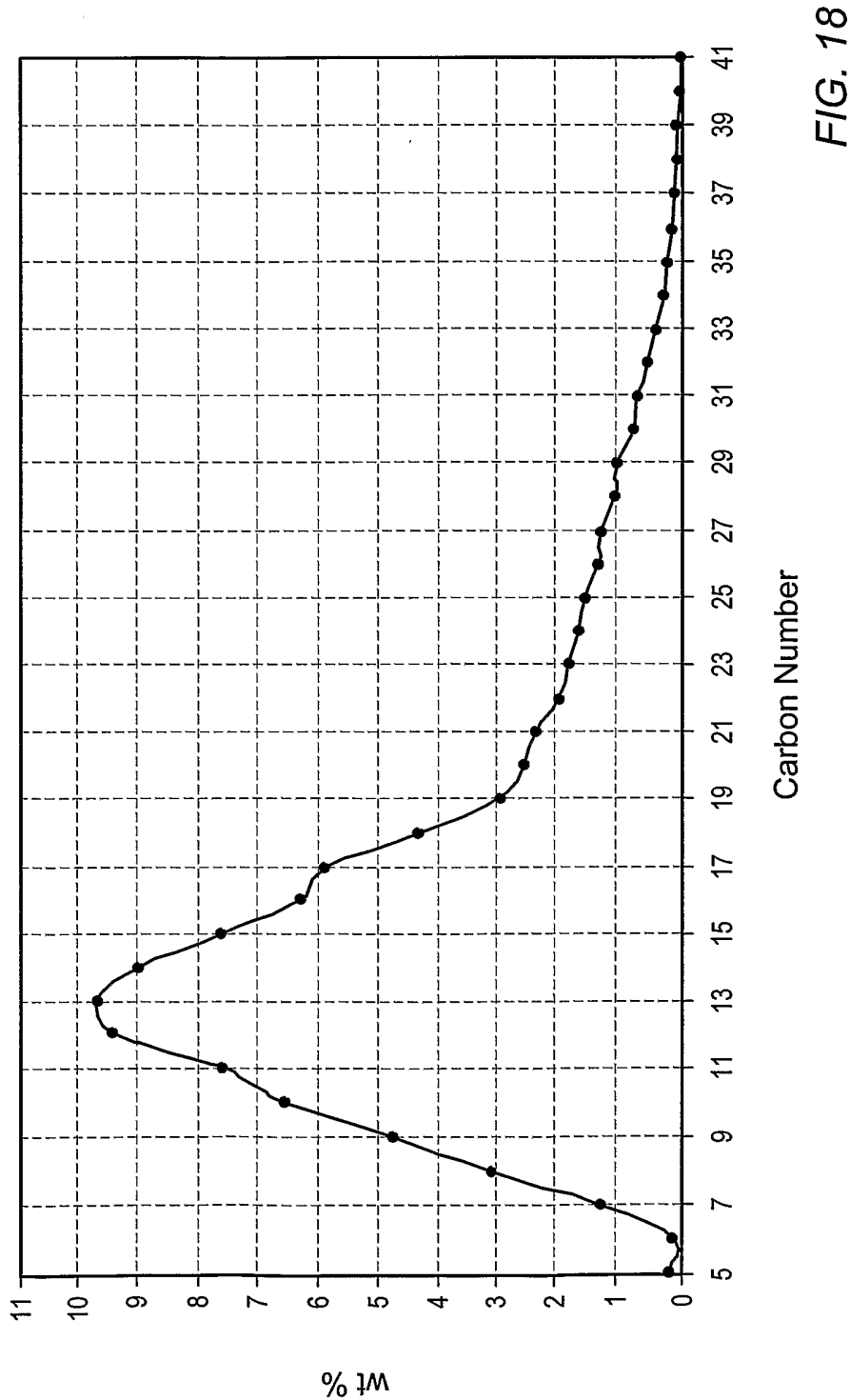


FIG. 17



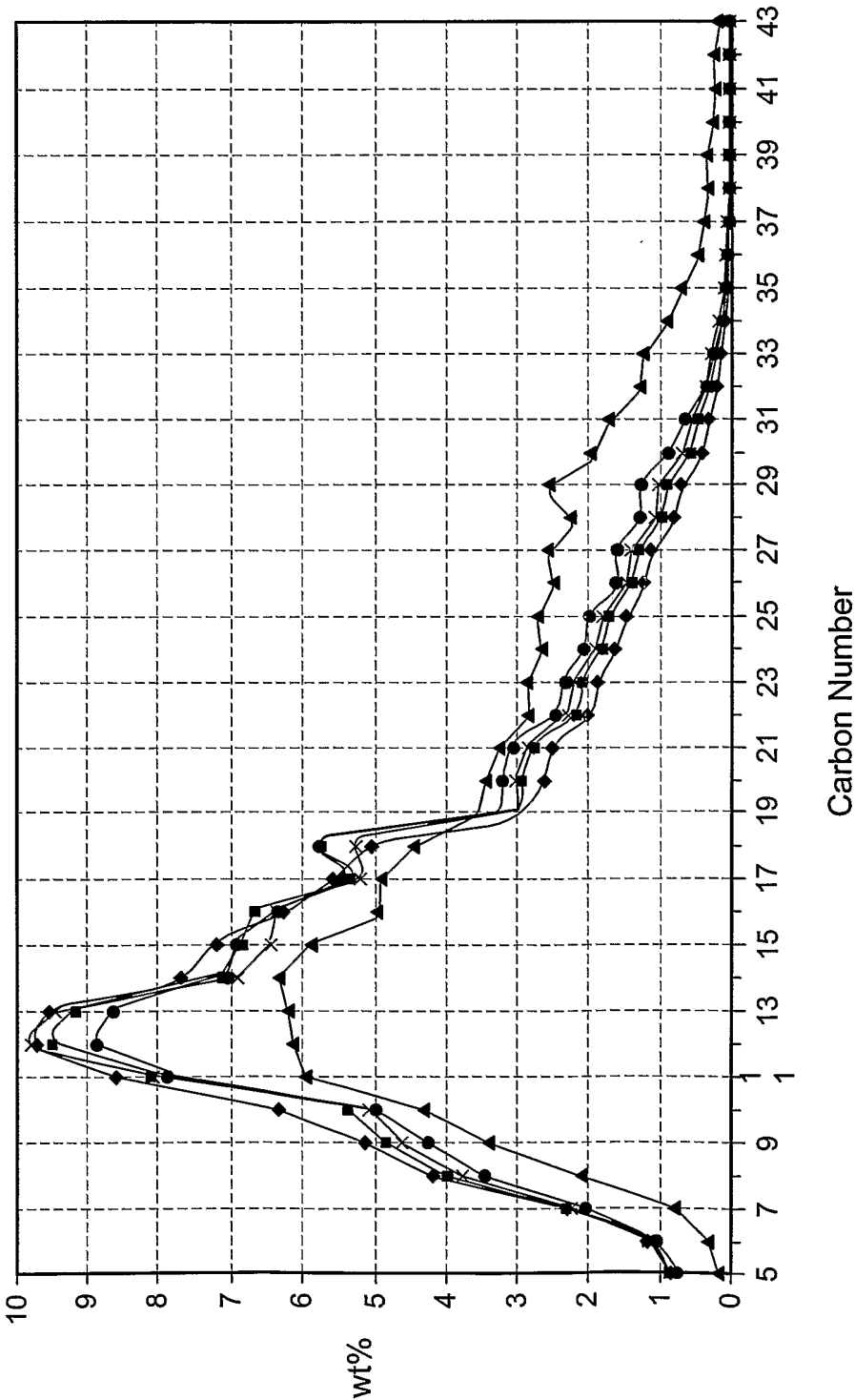


FIG. 19