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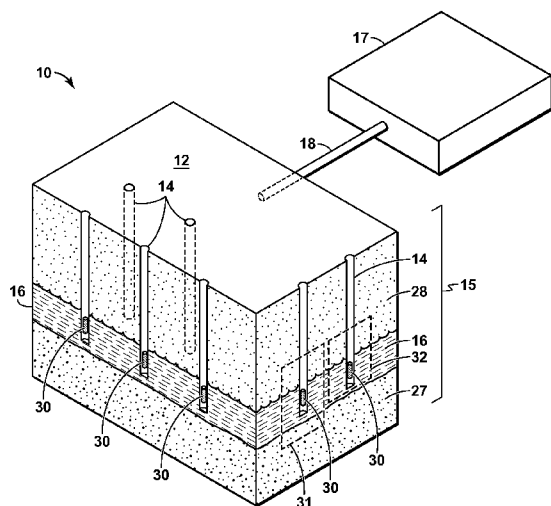
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- as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))

[Continued on next page]

(54) **Title:** CONTROLLED DELIVERY OF HEAT APPLIED TO A SUBSURFACE FORMATION**FIG. 5**

(57) **Abstract:** The present disclosure provides a method for controlling delivery of heat to a subsurface formation that includes (a) heating a first heater pattern; (b) determining an expected electrical conductivity; (c) calculating an estimated electrical conductivity; (d) comparing an estimated electrical conductivity to the expected electrical conductivity until the estimated electrical conductivity equals the expected electrical conductivity; (e) determining a first heater pattern reaction extent when the estimated electrical conductivity equals the expected electrical conductivity; and (f) when the first heater pattern reaction extent is within a target coke first heater pattern reaction extent range, one of (i) heating a second heater pattern instead of the first heater pattern and (ii) modifying the heating of the first heater pattern, and when the first heater pattern reaction extent is outside of the target coke first heater pattern reaction extent range repeating steps (a) - (e).



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CONTROLLED DELIVERY OF HEAT APPLIED TO A SUBSURFACE FORMATION**CROSS-REFERENCE TO RELATED APPLICATION**

[0001] This application claims the priority benefit of U.S. Provisional Patent Application 62/031093 filed 30 July 2014 entitled CONTROLLED DELIVERY OF HEAT APPLIED TO A SUBSURFACE FORMATION, the entirety of which is incorporated by reference herein.

BACKGROUND**Fields of Disclosure**

[0002] The disclosure relates generally to the field of hydrocarbon recovery from subsurface formations and, more particularly, to controlling delivery of heat applied to a subsurface formation.

Description of Related Art

[0003] This section is intended to introduce various aspects of the art, which may be associated with the present disclosure. This discussion is believed to assist in providing a framework to facilitate a better understanding of particular aspects of the present disclosure. Accordingly, it should be understood that this section should be read in this light, and not necessarily as admissions of prior art.

[0004] Modern society is greatly dependent on the use of hydrocarbons for fuels and chemical feedstocks. Subterranean formations that can be termed “reservoirs” may contain resources, such as hydrocarbons, that can be recovered. Removing hydrocarbons from the subterranean reservoirs depends on numerous physical properties of the subterranean rock formations, such as the permeability of the rock containing the hydrocarbons, the ability of the hydrocarbons to flow through the subterranean rock formations, and the proportion of hydrocarbons present, among other things.

[0005] Easily produced sources of hydrocarbons are dwindling, resulting in increased reliance on less conventional sources (i.e., unconventional resources) to satisfy future needs. Examples of unconventional resources may include but are not limited to heavy oil, tar and oil shale. The unconventional resources may be found in subsurface formations. For example, oil

shale may be found in a subsurface formation referred to as an oil shale formation because the subsurface formation contains oil shale. The world contains a substantial amount of unconventional resources. For example, the U.S. is estimated to contain over 4 billion barrels of oil (GBO) in-place.

[0006] Despite the substantial amount of unconventional resources in place, surface access to unconventional resources may be difficult. *In situ* conversion techniques that apply heat to unconventional resources offer the potential to access unconventional resources. *In situ* conversion techniques that apply heat to unconventional resources may be referred to as thermal processes. *In situ* conversion techniques refer to methods of producing and/or generating hydrocarbons from a subsurface formation in the original location or position of an unconventional resource.

[0007] Applying a thermal process to an unconventional resource may thermally decompose the unconventional resource to form gas hydrocarbons, liquid hydrocarbons and coke. For example, applying heat to oil shale may thermally decompose kerogen within the oil shale to form gas hydrocarbons, liquid hydrocarbons and coke. Continued application of heat via a thermal process to coke may cause the coke to undergo pyrolysis. Hydrogen and methane may be produced when the coke undergoes pyrolysis. The production of the hydrogen and methane may lead to a purified coke with a lower hydrogen to carbon ratio than is present in the unconventional resource before applying heat. The purified coke is coke that has been substantially dehydrogenated.

[0008] Energy required to convert a specified volume of an unconventional resource to a flowable hydrocarbon, when applying a thermal process to an unconventional resource, is governed by rock properties of the subsurface formation which contains the unconventional resource. The advantageous affects of one *in situ* conversion technique over another may be governed by how efficient it is for an *in situ* conversion technique to deliver energy to the subsurface formation containing the unconventional resource. Rock properties of the subsurface formation may include properties of the subsurface formation that can be measured and/or calculated. Examples of rock properties include but are not limited to electrical conductivity.

[0009] While applying heat to an unconventional resource, and as shown in Figure 1, an electrical conductivity of the unconventional resource may increase by several orders of

magnitude. Figure 1 shows that electrical conductivity of an unconventional resource may increase by several orders of magnitude for three different heating rates – a small heating rate 51, a moderate heating rate 52 and a large heating rate 53. The heating rate refers to the increase in the temperature that the unconventional resource experiences per unit time. The increase in electrical conductivity by several orders of magnitude may be due to the pyrolysis of the coke and the subsequent substantial dehydrogenation of the coke. The electrical conductivity may decrease after increasing by several orders of magnitude. The electrical conductivity decreases when carbonate minerals decompose and release carbon dioxide (CO₂) that may gasify coke.

[0010] The electrical conductivity of an unconventional resource, while applying a thermal process to the unconventional resource, is a function of temperature and a reaction extent of coke (ϵ_{coke}) – interchangeably referred to as coke reaction extent – that has been pyrolyzed (ϵ_{coke}) (Figure 2). Figure 2 shows the electrical conductivity 62 and temperature 61 of an oil shale sample that was heated in cycles and held isothermal at specific temperatures over time. Figure 2 shows that when the oil shale sample is heated from about 0 hours to about 8 hours, the electrical conductivity of the oil shale changes because the temperature and the reaction extent change. In other words, from about 0 hours to about 8 hours, the electrical conductivity is temperature dependent and reaction extent dependent. Figure 2 shows that from about 8 hours to about 24 hours, even though the reaction extent remains the same, the electrical conductivity changes because the temperature changes. In other words, Figure 2 shows that from about 8 hours to about 24 hours, the electrical conductivity is temperature dependent. Figure 2 shows that from about 24 hours to about 34 hours, even though the temperature remains the same, the electrical conductivity changes because the reaction extent changes. In other words, Figure 2 shows that from about 24 hours to about 34 hours, the electrical conductivity is reaction extent dependent.

[0011] While it is known that the electrical conductivity of some unconventional resources, while applying a thermal process to these unconventional resource, is a function of temperature and a reaction extent of coke that has been pyrolyzed, it is not known how to interpret the data for electrical conductivity of these unconventional resources as a function of temperature and reaction extent of coke that has been pyrolyzed; it is also not known how to trigger heating or cooling strategies of the unconventional resource based on the properties of the subsurface formation.

[0012] A need exists for improved technology, including technology that may address one or more of the above described disadvantages. For example, a need exists for controlling delivery of heat applied to a subsurface formation during a thermal process. Controlling the delivery of heat applied to the subsurface formation during a thermal process may be aided by the ability to interpret the data for electrical conductivity of an unconventional resources as a function of temperature and reaction extent of coke that has been pyrolyzed. Controlling the delivery of heat applied to the subsurface formation during a thermal process may be aided by knowing how to trigger heating or cooling strategies of an unconventional resource based on properties of the subsurface formation.

SUMMARY

[0013] The present disclosure may provide a method for controlling delivery of heat to a subsurface formation. The method may comprise (a) heating a first heater pattern in the subsurface formation using a heater; (b) determining an expected electrical conductivity of the first heater pattern; (c) calculating an estimated electrical conductivity; (d) comparing an estimated electrical conductivity of the first heater pattern to the expected electrical conductivity until the estimated electrical conductivity equals the expected electrical conductivity; (e) determining a first heater pattern reaction extent of the first heater pattern when the estimated electrical conductivity equals the expected electrical conductivity; and (f) when the first heater pattern reaction extent is within a target coke first heater pattern reaction extent range, one of (i) heating a second heater pattern instead of the first heater pattern and (ii) modifying the heating of the first heater pattern, and when the first heater pattern reaction extent is outside of the target coke first heater pattern reaction extent range repeating steps (a) – (e).

[0014] The present disclosure may provide a method for producing hydrocarbons from a subsurface formation while controlling delivery of heat to the subsurface formation. The method may comprise (a) heating a first heater pattern in the subsurface formation using a heater; (b) determining an expected electrical conductivity of the first heater pattern; (c) calculating an estimated electrical conductivity; (d) comparing an estimated electrical conductivity of the first heater pattern to the expected electrical conductivity until the estimated electrical conductivity equals the expected electrical conductivity; (e) determining a first heater pattern reaction extent of the first heater pattern when the estimated electrical conductivity equals the expected

electrical conductivity; and (f) when the first heater pattern reaction extent is within a target coke first heater pattern reaction extent range, one of (i) heating a second heater pattern instead of the first heater pattern and (ii) modifying the heating of the first heater pattern, and when the first heater pattern reaction extent is outside of the target coke first heater pattern reaction extent range repeating steps (a) – (e); (g) mobilizing the hydrocarbons from at least one of the first heater pattern and the second heater pattern by heating the hydrocarbons; and (h) producing the hydrocarbons.

[0015] The foregoing has broadly outlined the features of the present disclosure so that the detailed description that follows may be better understood. Additional features will also be described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] These and other features, aspects and advantages of the present disclosure will become apparent from the following description and the accompanying drawings, which are described briefly below.

[0017] Figure 1 is a diagram of electrical conductivity trends.

[0018] Figure 2 is a diagram of oil shale temperature and electrical conductivity trends.

[0019] Figure 3 is a diagram showing electrical conductivity as a function of temperature for specific coke reaction extent.

[0020] Figure 4A is a map of electrical conductivity within a subsurface formation.

[0021] Figure 4B is a map of electrical conductivity within a subsurface formation.

[0022] Figure 5 is a front view of a subsurface formation.

[0023] Figure 6 is a schematic of methods of the present disclosure.

[0024] It should be noted that the figures are merely examples and that no limitations on the scope of the present disclosure are intended hereby. Further, the figures are generally not drawn to scale but are drafted for the purpose of convenience and clarity in illustrating various aspects of the disclosure.

DETAILED DESCRIPTION

[0025] For the purpose of promoting an understanding of the principles of the disclosure, reference will now be made to the features illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the disclosure is thereby intended. Any alterations and further modifications, and any further applications of the principles of the disclosure as described herein are contemplated as would normally occur to one skilled in the art to which the disclosure relates. It will be apparent to those skilled in the relevant art that some features that are relevant to the present disclosure may not be shown in the drawings for the sake of clarity.

[0026] At the outset, for ease of reference, certain terms used in this application and their meaning as used in this context are set forth below. To the extent a term used herein is not defined below, it should be given the broadest definition persons in the pertinent art have given that term as reflected in at least one printed publication or issued patent. Further, the present processes are not limited by the usage of the terms shown below, as all equivalents, synonyms, new developments and terms or processes that serve the same or a similar purpose are considered to be within the scope of the present disclosure.

[0027] As used herein, the term “electrical conductivity” refers to the ability of a material to conduct electricity. Electrical conductivity is the inverse of resistivity. The electrical conductivity is a property of a material.

[0028] As used herein, the term “hydrocarbon” refers to an organic compound that includes primarily, if not exclusively, the elements hydrogen and carbon. Hydrocarbons may also include other elements, such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur. Hydrocarbons generally fall into two classes: aliphatic, or straight chain hydrocarbons, and cyclic, or closed ring hydrocarbons, including cyclic terpenes. Examples of hydrocarbon-containing materials include any form of natural gas, oil, coal, heavy oil and kerogen that can be used as a fuel or upgraded into a fuel.

[0029] As used herein, the terms “produced fluids” and “production fluids” refer to liquids and/or gases removed from a subsurface formation, including, for example, an organic-rich rock formation. Produced fluids may include both hydrocarbon fluids and non-hydrocarbon fluids. Production fluids may include, but are not limited to, liquids and/or gases originating from

pyrolysis of oil shale, natural gas, synthesis gas, a pyrolysis product of coal, carbon dioxide, hydrogen sulfide and water (including steam).

[0030] As used herein, the term “fluid” refers to gases, liquids, and combinations of gases and liquids, as well as to combinations of gases and solids, and combinations of liquids and solids.

[0031] As used herein, the term “formation hydrocarbons” refers to both light and/or heavy hydrocarbons and solid hydrocarbons that are contained in an organic-rich rock formation. Formation hydrocarbons may be, but are not limited to, natural gas, oil, kerogen, oil shale, coal, tar, natural mineral waxes, and asphaltenes.

[0032] As used herein, the term “gas” refers to a fluid that is in its vapor phase at 1 atmosphere (atm) and 15 degrees Celsius (° C).

[0033] As used herein, the term “kerogen” refers to a solid, insoluble hydrocarbon that may principally contain carbon, hydrogen, nitrogen, oxygen, and/or sulfur.

[0034] As used herein, the term “oil” refers to a hydrocarbon fluid containing primarily a mixture of condensable hydrocarbons.

[0035] As used herein, the term “oil shale” refers to any fine-grained, compact, sedimentary rock containing organic matter made up mostly of kerogen, a high-molecular weight solid or semi-solid substance that is insoluble in petroleum solvents and is essentially immobile in its rock matrix.

[0036] As used herein, the term “organic-rich rock” refers to any rock matrix holding solid hydrocarbons and/or heavy hydrocarbons. Rock matrices may include, but are not limited to, sedimentary rocks, shales, siltstones, sands, silicities, carbonates, and diatomites. Organic-rich rock may contain kerogen.

[0037] As used herein, the term “organic-rich rock formation” refers to any formation containing organic-rich rock. Organic-rich rock formations include, for example, oil shale formations, coal formations, tar sands formations or other formation hydrocarbons.

[0038] As used herein, “overburden” refers to the material overlying a subterranean reservoir. The overburden may include rock, soil, sandstone, shale, mudstone, carbonate and/or ecosystem above the subterranean reservoir. During surface mining the overburden is removed prior to the start of mining operations. The overburden may refer to formations above or below

free water level. The overburden may include zones that are water saturated, such as fresh or saline aquifers. The overburden may include zones that are hydrocarbon bearing.

[0039] As used herein, “permeability” is the capacity of a rock to transmit fluids through the interconnected pore spaces of the structure. A customary unit of measurement for permeability is the milliDarcy (mD). The term “absolute permeability” is a measure for transport of a specific, single-phase fluid through a specific portion of a formation. The term “relative permeability” is defined for relative flow capacity when one or more fluids or one or more fluid phases may be present within the pore spaces, in which the interference between the different fluid types or phases competes for transport within the pore spaces within the formation. The different fluids present within the pore spaces of the rock may include water, oil and gases of various compositions. Fluid phases may be differentiated as immiscible fluids, partially miscible fluids and vapors. The term “low permeability” is defined, with respect to subsurface formations or portions of subsurface formations, as an average permeability of less than about 10 mD.

[0040] As used herein, the term “pyrolysis” or “pyrolyze” refers to the breaking of chemical bonds through the application of heat. For example, pyrolysis may include transforming a compound into one or more other substances by heat alone or by heat in combination with an oxidant. Pyrolysis may include modifying the nature of the compound by addition of hydrogen atoms which may be obtained from molecular hydrogen, water, carbon dioxide, or carbon monoxide. Heat may be transferred to a section of the formation to cause pyrolysis.

[0041] As used herein, the term “reaction extent” refers to how far along a reaction has progressed for a given reaction or a given set of reactions.

[0042] As used herein, “reservoir” or “subterranean reservoir” is a subsurface rock or sand formation from which a production fluid or resource can be harvested. The rock formation may include sand, granite, silica, carbonates, clays, and organic matter, such as oil shale, light or heavy oil, gas, or coal, among others. Reservoirs can vary in thickness from less than one foot (0.3048 meter (m)) to hundreds of feet (hundreds of meters).

[0043] As used herein, the term “solid hydrocarbons” refers to any hydrocarbon material that is found naturally in substantially solid form at formation conditions. Non-limiting examples include kerogen, coal, shungites, asphaltites, and natural mineral waxes.

[0044] As used herein “subsurface formation” or “subterranean formation” refers to the material existing below the Earth’s surface. The subsurface formation may interchangeably be referred to as a formation or a subterranean formation. The subsurface formation may comprise a range of components, e.g. minerals such as quartz, siliceous materials such as sand and clays, as well as the oil and/or gas that is extracted.

[0045] As used herein, “substantial,” “about” and “approximate” when used in reference to a quantity or amount of a material, or a specific characteristic of the material, refers to an amount that is sufficient to provide an effect that the material or characteristic was intended to provide. The exact degree of deviation allowable may in some cases depend on the specific context.

[0046] As used herein, the term “tar” refers to a viscous hydrocarbon that generally has a viscosity greater than about 10,000 centipoise (cP) at 15° C. The specific gravity of tar generally is greater than 1.000. Tar may have an American Petroleum Institute (API) gravity less than 10 degrees. “Tar sands” refers to a formation that has tar in it. In contrast, light oil may have a viscosity less than 10 cP; medium oil and heavy oil may have a viscosity of 10 cP and greater, up to or exceeding 10,000 cP.

[0047] As used herein, “underburden” refers to the material underlying a subterranean reservoir. The underburden may include rock, soil, sandstone, shale, mudstone, wet/tight carbonate and/or ecosystem below the subterranean reservoir.

[0048] As used herein, “wellbore” is a hole in the subsurface formation made by drilling or inserting a conduit into the subsurface. A wellbore may have a substantially circular cross section or any other cross-section shape, such as an oval, a square, a rectangle, a triangle, or other regular or irregular shapes. The term “well,” when referring to an opening in the formation, may be used interchangeably with the term “wellbore.” Further, multiple pipes may be inserted into a single wellbore, for example, as a liner configured to allow flow from an outer chamber to an inner chamber.

[0049] As used herein, the term “coupled” means the joining of two members directly or indirectly to one another. Such joining may be stationary or moveable in nature. Such joining may be achieved with the two members or the two members and any additional intermediate members being integrally formed as a single unitary body with one another or with the two

members or the two members and any additional intermediate members being attached to one another. Such joining may be permanent in nature or may be removable or releasable in nature.

[0050] The articles “the”, “a” and “an” are not necessarily limited to mean only one, but rather are inclusive and open ended so as to include, optionally, multiple such elements.

[0051] “At least one,” in reference to a list of one or more entities should be understood to mean at least one entity selected from any one or more of the entity in the list of entities, but not necessarily including at least one of each and every entity specifically listed within the list of entities and not excluding any combinations of entities in the list of entities. This definition also allows that entities may optionally be present other than the entities specifically identified within the list of entities to which the phrase “at least one” refers, whether related or unrelated to those entities specifically identified. Thus, as a non-limiting example, “at least one of A and B” (or, equivalently, “at least one of A or B,” or, equivalently “at least one of A and/or B”) may refer, to at least one, optionally including more than one, A, with no B present (and optionally including entities other than B); to at least one, optionally including more than one, B, with no A present (and optionally including entities other than A); to at least one, optionally including more than one, A, and at least one, optionally including more than one, B (and optionally including other entities). In other words, the phrases “at least one,” “one or more,” and “and/or” are open-ended expressions that are both conjunctive and disjunctive in operation. For example, each of the expressions “at least one of A, B and C,” “at least one of A, B, or C,” “one or more of A, B, and C,” “one or more of A, B, or C” and “A, B, and/or C” may mean A alone, B alone, C alone, A and B together, A and C together, B and C together, A, B and C together, and optionally any of the above in combination with at least one other entity.

[0052] The disclosure relates to systems and methods for controlling delivery of heat applied to a subsurface formation. Figures 1-6 of the disclosure display various aspects of the systems and methods.

[0053] The systems 10 and methods 100 may include heating a first heater pattern 31 in a subsurface formation 15 using a heater 30, 101 (Figures 5-6). The subsurface formation 15 may comprise an overburden 28, a subterranean reservoir 16, and an underburden 27. The hydrocarbons may be within the subterranean reservoir 16. The top of the subsurface formation 15 may be a surface 12. The surface may be the Earth’s surface.

[0054] The heater 30 may heat hydrocarbons within the subsurface formation 15. The hydrocarbons may be referred to as formation hydrocarbons. The heater 30 may heat hydrocarbons within the subterranean reservoir 16 of the subterranean formation 15. The heater 30 may heat the hydrocarbons by generating heat. The heater 30 may generate heat when power transmitted to the heater 30 reaches the heater 30. The power may be transmitted in any suitable way. The power transmitted may be defined as any component of energy, such as but not limited to magnitude or frequency. The heater 30 may conduct electricity. The heater 30 may have an electrical conductivity.

[0055] The heater 30 may comprise heaters. Each of the heaters 30 may require power to generate heat. The heaters 30 may be controlled as a system or independently. One or more of the heaters 30 may be within the first heater pattern 31. The first heater pattern 31 may be the area that the one or more heaters 30 within the first heater pattern heat. The first heater pattern 31 may span any area within the subsurface formation 15. The first heater pattern 31 may form any shape within the subsurface formation 15.

[0056] The subsurface formation may include a second heater pattern 32. The second heater pattern 32 may include one or more heaters 30. The second heater pattern 32 may be separate and distinct from the first heater pattern 31. If the second heater pattern 32 is separate from the first heater pattern 31, the one or more heaters 30 within the second heater pattern 32 may be separate from the one or more heaters 30 within the first heater pattern 31. As shown in Figure 5, for example, the first heater pattern 31 is separate from the second heater pattern 32 and the first heater pattern 31 includes one of the heaters 30 while the second heater pattern 32 includes another of the heaters 30; the first heater pattern 31 is adjacent to the second heater pattern 32 but spaced apart from the second heater pattern 32. The second heater pattern 32 may abut the first heater pattern 31. The second heater pattern 32 may overlap at least a portion of the first heater pattern 31. If the second heater pattern 32 overlaps at least the portion of the first heater pattern 31, at least a portion of the one or more heaters 30 within the second heater pattern 32 may be within the first heater pattern 31. The second heater pattern 32 may span any area within the subsurface formation 15. The second heater pattern 32 may form any shape within the subsurface formation 15.

[0057] The systems 10 and methods 100 may include determining an expected electrical conductivity of the first heater pattern 31, 102 (Figure 6). The expected electrical conductivity of the first heater pattern 31 may be determined by any suitable method. For example, the expected electrical conductivity of the first heater pattern 31 may be determined using electrical resistive tomography (ERT). ERT is a method to spatially map a resistivity volume of a component by applying a known current to a first electrode in contact with a formation of interest and by measuring the induced voltage potential between second electrodes in contact with the formation of interest. The component may be the heater 30, a wellbore not used for heating, a production wellbore or an observation wellbore. An observation wellbore may be a wellbore used to observe what occurs in the subsurface formation 15. An observation wellbore may not heat or produce hydrocarbons. An observation wellbore may measure data within the subsurface formation 15. The formation of interest may be any or all of the subsurface formation 15 (e.g., the subsurface reservoir 16, the subsurface reservoir 16 and the overburden 28, the subsurface reservoir 16 and the underburden 27). If the formation of interest is the subsurface formation 15, the first electrode may be in contact with the formation of interest. If the formation of interest is the subsurface formation 15, the second electrodes may be in contact with the formation of interest. The mathematical basis for ERT is based on Poisson's equation:

$$-\nabla(\sigma\nabla\phi)=0 \quad (1).$$

Poisson's equation may be solved in a piecewise continuous fashion for the formation of interest. In equation (1), σ is the electrical conductivity, ϕ is the voltage potential and ∇ is the Laplace operator. The solution to equation (1) may be subject to the following boundary condition:

$$\sigma_s \bar{n} \cdot \nabla \phi = J_s \quad (2).$$

In equation (2), $\bar{n}$ is a unit normal vector defining a face of the control volume and J_s is a density at a surface of each control volume. Equation (2) depicts that the current density at the surface of each control volume J_s is proportional to a voltage potential gradient across the control volume and the electrical conductivity of the control volume. Using multiple measurements of ϕ and J it is possible to determine spatially the formation of interest's electrical conductivity. The control volume is an infinitesimally small portion of the formation of interest. The control volume is a way to mathematically describe the entire formation of

interest”so that electrical conductivity can be solved for at each discrete control volume within the formation of interest.

[0058] Conventional technology has used ERT. But the conventional technology has failed to recognize that substantial changes to the electrical conductivity of a subsurface formation may be associated with chemical reactions attributable to hydrocarbon conversion. Conventional technology has failed to identify how to interpret ERT data for reaction extent and how specific values trigger specific responses.

[0059] While the above discussion focuses on how to determine an expected electrical conductivity of the first heater pattern 31, an expected electrical conductivity of the second heater pattern 32 may be determined by any of the methods that can be used to determine the expected electrical conductivity of the first heater pattern 31. If the subsurface formation 15 contains more than the first heater pattern 31 and the second heater pattern 32 (e.g., a third heater pattern, a fourth heater pattern), each of the other heater patterns (e.g., a third heater pattern, a fourth heater pattern) may be determined by any of the methods that can be used to determine the expected electrical conductivity of the first heater pattern 31 and/or the second heater pattern 32.

[0060] The systems 10 and methods 100 may include calculating an estimated electrical conductivity, 103 (Figure 4). Calculating the estimated electrical conductivity may comprise determining how an experimental electrical conductivity changes as a function of an experimental coke heater pattern reaction extent and an experimental temperature. Determining how the experimental electrical conductivity changes may comprise using a functional relationship.

[0061] The functional relationship has been conventionally thought to be equal to the following equation:

$$\sigma = Ae^{BT} \quad (3)$$

In equation (3), A is a first functional relationship, B is a second functional relationship, e is an exponential function, T is temperature and σ is electrical conductivity. Using equation (3) to calculate the estimated electrical conductivity does not yield a correctly calculated estimated electrical conductivity for a subterranean formation that is governed by the characteristics shown in Figure 2. Namely, using equation (3) to calculate the estimate electrical conductivity does not

yield a correctly calculated estimated electrical conductivity for a subterranean formation whose electrical conductivity is a function of temperature and reaction extent of coke. The present inventors determined that equation (3) yields an incorrectly estimate electrical conductivity for a subterranean formation, which is governed by the characteristics shown in Figure 2, because equation (3) does not enable the decoupling of electrical conductivity's dependence on temperature from the reaction extent of coke.

[0062] The present inventors determined that the functional relationship having the following equation correctly estimates electrical conductivity for a subterranean formation governed by the characteristics shown in Figure 2:

$$\sigma = A(\varepsilon_{coke})e^{B(\varepsilon_{coke})T} \quad (4)$$

In equation (4), A is a first functional relationship, B is a second functional relationship, e is an exponential function, T is temperature, σ is electrical conductivity, ε_{coke} is a coke heater pattern reaction extent, $A(\varepsilon_{coke})$ is that the first functional relationship is a function of the coke heater pattern reaction extent and $B(\varepsilon_{coke})$ is that the second functional relationship is a function of the coke heater pattern reaction extent. The first functional relationship is a constant obtained from experimentation. The second functional relationship is a constant obtained from experimentation. The temperature may be referred to as an experimental temperature. The electrical conductivity may be referred to as an estimated electrical conductivity. The coke heater pattern reaction extent may be referred to as an experimental coke heater pattern reaction extent.

[0063] The functional relationship shown in equation (4) may be determined by conducting experiments at a constant experimental reaction extent or a constant experimental temperature such that the effects of the experimental temperature and the experimental reaction extent on the experimental electrical conductivity can be decoupled. When conducting experiments at a constant experimental reaction extent, the experimental electrical conductivity changes as a function of the experimental temperature for the constant experimental reaction extent. For example, as shown in Figure 3, the experimental electrical conductivity changes as a function of the experimental temperature for six different experimental reaction extents. The six experimental reaction extents are held constant. Each of the six experimental reaction extents is a different experimental reaction extent numerical value from the other five experimental

reaction extents. When the experimental reaction extents are held constant, the experimental temperature changes. The changing experimental temperature for the six experimental reaction extents is shown by line 71, line 72, line 73, line 79, line 75 and line 76. When conducting experiments at a constant experimental temperature, the experimental electrical conductivity changes as a function of the experimental reaction extent for the constant experimental temperature. When an experimental temperature is held constant, the experimental reaction extent will change. If the experimental reaction extent and the experimental temperature are not held constant, as shown via line 78 in Figure 3, the effects of experimental temperature and experimental reaction extent on experimental electrical conductivity cannot be decoupled.

[0064] Calculating the estimated electrical conductivity may comprise calculating the first functional relationship and the second functional relationship. The first functional relationship and the second functional relationship may be obtained by regression. The regression may comprise linear regression. If experiments are conducted with constant experimental reaction extents, as shown in Figure 3, the first functional relationship and the second functional relationship may be obtained by regressing a plot, such as that of Figure 3, that shows the experimental electrical conductivities for constant experimental reaction extents and varying experimental temperatures. If the experiments are conducted with constant experimental temperatures, the first functional relationship and the second functional relationship may be obtained by regressing the plot showing the experimental electrical conductivities for constant experimental temperatures and varying experimental reaction extents.

[0065] Calculating the estimated electrical conductivity may comprise using the functional relationship depicted in equation (4), the first functional characteristic, the second functional characteristic and one of an estimated temperature and an estimated first heater pattern reaction extent. Specifically, calculating the estimated electrical conductivity may comprise inputting the first functional characteristic, the second functional characteristic and one of the estimated temperature and the estimated first heater pattern reaction extent into the functional relationship depicted in equation (4) to calculate the estimate electrical conductivity. The estimated temperature may be any temperature value. The estimated first heater pattern reaction extent may be any reaction extent. The estimated temperature may be determined by an operator. The first heater pattern reaction extent may be determined by an operator. The operator may be a person or a mechanism for performing operations.

[0066] The systems 10 and methods 100 may comprise comparing the estimated electrical conductivity of the first heater pattern 31 to the expected electrical conductivity of the first heater pattern 31 until the estimated electrical conductivity equals the expected electrical conductivity, 104 (Figure 4). When comparing the estimated electrical conductivity to the expected electrical conductivity, the estimated electrical conductivity may be calculated by inputting the first functional characteristic, the second functional characteristic and one of a first estimated temperature and a first estimated first heater pattern reaction extent into the functional relationship depicted in equation (4). The estimated electrical conductivity that is calculated may be what is compared to the expected electrical conductivity. If the calculated estimated electrical conductivity equals the expected electrical conductivity, there is no need to calculate another estimated electrical conductivity. If the estimated electrical conductivity does not equal the expected electrical conductivity, another estimated electrical conductivity may be calculated by inputting the first functional characteristic, the second functional characteristic and one of a second estimated temperature and a second estimated first heater pattern reaction extent into the functional relationship depicted in equation (4). If the estimated electrical conductivity calculated using the one of the second estimated temperature and the second estimated first heater pattern reaction extent equals the expected electrical conductivity, there is no need to calculate another estimated electrical conductivity. If the estimated electrical conductivity calculated using the one of the second estimated temperature and the second estimated first heater pattern reaction extent does not equal the expected electrical conductivity, another estimated electrical conductivity must be calculated by inputting the first functional characteristic, the second functional characteristic and one of a third estimated temperature and a third estimated first heater pattern reaction extent into the functional relationship depicted in equation (4). This process of calculating an estimated electrical conductivity and comparing it to the expected electrical conductivity may continue until the estimated electrical conductivity equals the expected electrical conductivity. The first estimated temperature, the second estimated temperature and the third estimated temperature may be different numerical values. In other words, the first estimated temperature may be a different numerical temperature from the second estimated temperature and the third estimated temperature, etc. The first estimated heater pattern reaction extent, the second estimated heater pattern reaction extent and the third estimated heater pattern reaction extent may be different numerical values. In other words, the

first estimated heater pattern reaction extent may be a different numerical reaction extent from the second estimated heater pattern reaction extent and the third estimated heater pattern reaction extent, etc.

[0067] The systems 10 and methods 100 may include determining one of a first heater pattern reaction extent and a first heater pattern temperature of the first heater pattern 31 when the estimated electrical conductivity equals the expected electrical conductivity, 105 (Figure 6). The first heater pattern reaction extent may be the reaction extent of the first heater pattern 31 within the subterranean formation. The first heater pattern temperature may be the temperature of the first heater pattern 31. The first heater pattern reaction extent may be the estimated first heater pattern reaction extent that allows the estimated electrical conductivity to equal the expected electrical conductivity. The first heater pattern temperature may be the estimated temperature that allows the estimated electrical conductivity to equal the expected electrical conductivity.

[0068] The systems 10 and methods 100 may include determining whether the first heater pattern reaction extent is within a target coke first heater pattern reaction extent range, 106 (Figure 6). The target coke first heater pattern reaction extent range may be a range of reaction extents indicative of overheating of the first heater pattern. Overheating of a heater pattern means that a substantial portion of the heater pattern has reached a reaction extent that is greater than zero.

[0069] When the first heater pattern reaction extent is within the target coke first heater pattern reaction extent range, a second heater pattern 32 may be heated instead of the first heater pattern 31 or the heating of the first heater pattern 31 may be modified. The target coke first heater pattern reaction extent range is the range of reaction extents that indicate a hydrocarbon has thermally decomposed to form coke within the first heater pattern 31. The first heater pattern reaction extent being within the target coke first heater pattern reaction extent range may be indicative of the overcooking – interchangeably referred to as overheating – of hydrocarbons within the first heater pattern 31. The first heater pattern reaction extent being within the target coke first heater pattern reaction extent range may be indicative of the hydrocarbons within the first heater pattern 31 almost being overheated by a heater 30. Each heater pattern (e.g., the first heater pattern, the second heater pattern) has a heater pattern reaction extent when it is heated and a target coke heater pattern reaction extent range. For example, the second heater pattern 32

when heated has a second heater pattern reaction extent and a target coke second heater pattern reaction extent range. The target coke heater pattern reaction extent range for each of these heater patterns is the range of reaction extents that indicate a hydrocarbon has thermally decomposed to form coke within the specific heater pattern in question.

[0070] When the first heater pattern reaction extent is outside of the first coke heater pattern reaction extent range, the steps of heating the first heater pattern 101, determining the expected electrical conductivity of the first heater pattern 102, calculating the estimated electrical conductivity 103, comparing the estimated electrical conductivity to the expected electrical conductivity 104 and determining the first heater pattern reaction extent 105 may be repeated. Repeating steps 101, 102, 103, 104 and 105 may terminate when the first heater pattern reaction extent is within the target coke first heater pattern reaction extent range.

[0071] The methods 10 and systems 100 may include mobilizing hydrocarbons from at least one of the first heater pattern 31 and the second heater pattern 32 by heating with the heater 30. The hydrocarbons within a heater pattern (e.g., the first heater pattern, the second heater pattern) may be mobilized while the hydrocarbons within the heater pattern are heated by a heater 30. As the hydrocarbons are mobilized they may flow to a production wellbore 14. Mobilizing the hydrocarbons may occur before, after or when heating the second heater pattern 32 instead of the first heater pattern 31. Mobilizing the hydrocarbons may occur before, after or when modifying the heating of the first heater pattern 31.

[0072] The methods 10 and systems 100 may include producing the hydrocarbons. Once produced, the hydrocarbons may be referred to as produced fluids. The hydrocarbons may be produced via the production wellbore 14. The hydrocarbons produced may be the hydrocarbons that are mobilized from the at least one of the first heater pattern 31 and the second heater pattern 32. The production wellbore 14 may be any suitable wellbore that is constructed to produce hydrocarbons. The hydrocarbons produced via the production wellbore 14 may be processed in a surface facility 17. The hydrocarbons may be processed in the surface facility 17 so that the hydrocarbons can be sold. The hydrocarbons may travel from the production wellbore 14 to the surface facility 17 via a pipeline 18 (Figure 5). Producing the hydrocarbons may occur before, after or when heating the second heater pattern 32 instead of the first heater pattern 31.

Producing the hydrocarbons may occur before, after or when modifying the heating of the first heater pattern 31.

[0073] The methods and systems disclosed in the present disclosure may be implemented for any heater pattern (e.g., a first heater pattern, a second heater pattern, a third heater pattern).

[0074] As a result of the methods and systems disclosed in the present disclosure, a subsurface formation may be heated better. The subsurface formation may be heated better because the methods and systems disclosed of the present disclosure help prevent overheating of a heater pattern. Figure 4A shows a tomography map of what is measured to occur in the subsurface formation. Figure 4B is a translation of electrical conductivity to reaction extent. Figure 4B is intended to reflect what is occurring in Figure 4A once the estimated electrical conductivity equals the expected electrical conductivity. Figures 4A and 4B show that the methods of the present disclosure, for considering the affects of chemical reaction kinetics on electrical conductivity more accurately predict reaction extent within the subsurface formation.

[0075] It is important to note that the elements and steps depicted in Figures 1-6 are provided for illustrative purposes only and a particular step may not be required to perform the inventive methodologies. The claims, and only the claims, define the inventive system and methodologies.

[0076] The method and system may include the mechanism for performing operations. The mechanism for performing operations may be specially constructed for the required purposes, or it may comprise a general-purpose computer selectively activated or reconfigured by a computer program stored in the general-purpose computer. Such a computer program may be stored in a computer-readable medium. The computer-readable medium may include any mechanism for storing or transmitting information in a form readable by a machine (e.g., a computer). The computer-readable (e.g., machine-readable) medium may include, but is not limited to, a machine (e.g., a computer) readable storage medium (e.g., read only memory ("ROM"), random access memory ("RAM"), magnetic disk storage media, optical storage media, flash memory devices, etc.), and a machine (e.g., computer) readable transmission medium (electrical, optical, acoustical or other form of propagated signals (e.g., carrier waves, infrared signals, digital signals, etc.)). The computer-readable medium may be non-transitory.

[0077] As will be apparent to one of ordinary skill in the relevant art, the modules, features, attributes, methodologies, and other aspects of the present disclosure can be implemented as

software, hardware, firmware or any combination of the three. Of course, wherever a component of the present disclosure is implemented as software, the component can be implemented as a standalone program, as part of a larger program, as a plurality of separate programs, as a statically or dynamically linked library, as a kernel loadable module, as a device driver, and/or in every and any other way known now or in the future to those of skill in the art of computer programming. The present disclosure is in no way limited to implementation in any specific operating system or environment.

[0078] Disclosed aspects of the present disclosure may be used in hydrocarbon management activities. “Hydrocarbon management” or “managing hydrocarbons” may include hydrocarbon extraction, hydrocarbon production, hydrocarbon exploration, identifying potential hydrocarbon resources, identifying well locations, determining well injection and/or extraction rates, identifying reservoir connectivity, acquiring, disposing of and/ or abandoning hydrocarbon resources, reviewing prior hydrocarbon management decisions, and any other hydrocarbon-related acts or activities. The term “hydrocarbon management” may be used for the injection or storage of hydrocarbons or CO₂, for example the sequestration of CO₂, such as reservoir evaluation, development planning, and reservoir management. The disclosed methodologies and techniques may be used to extract hydrocarbons from a subsurface region. Hydrocarbon extraction may be conducted to remove hydrocarbons from the subsurface region, which may be accomplished by drilling a well using oil drilling equipment. The equipment and techniques used to drill a well and/or extract the hydrocarbons are well known by those skilled in the relevant art. Other hydrocarbon extraction activities and, more generally, other hydrocarbon management activities, may be performed according to known principles.

[0079] It should be noted that the orientation of various elements may differ, and that such variations are intended to be encompassed by the present disclosure. It is recognized that features of the disclosure may be incorporated into other examples.

[0080] It should be understood that the preceding is merely a detailed description of this disclosure and that numerous changes, modifications, and alternatives can be made in accordance with the disclosure here without departing from the scope of the disclosure. The preceding description, therefore, is not meant to limit the scope of the disclosure. Rather, the scope of the disclosure is to be determined only by the appended claims and their equivalents. It is also

contemplated that structures and features embodied in the present examples can be altered, rearranged, substituted, deleted, duplicated, combined, or added to each other.

CLAIMS

What is claimed is:

1. A method for controlling delivery of heat applied to a subsurface formation, comprising:

- (a) heating a first heater pattern in the subsurface formation using a heater;
- (b) determining an expected electrical conductivity of the first heater pattern;
- (c) calculating an estimated electrical conductivity;
- (d) comparing an estimated electrical conductivity of the first heater pattern to the expected electrical conductivity until the estimated electrical conductivity equals the expected electrical conductivity;
- (e) determining a first heater pattern reaction extent of the first heater pattern when the estimated electrical conductivity equals the expected electrical conductivity; and
- (f) when the first heater pattern reaction extent is within a target coke first heater pattern reaction extent range, one of (i) heating a second heater pattern instead of the first heater pattern and (ii) modifying the heating of the first heater pattern, and

when the first heater pattern reaction extent is outside of the target coke first heater pattern reaction extent range repeating steps (a) – (e).

2. A method for producing hydrocarbons from a subsurface formation while controlling delivery of heat applied to the subsurface formation, comprising:

- (a) heating a first heater pattern in the subsurface formation using a heater;
- (b) determining an expected electrical conductivity of the first heater pattern;
- (c) calculating an estimated electrical conductivity;
- (d) comparing an estimated electrical conductivity of the first heater pattern to the expected electrical conductivity until the estimated electrical conductivity equals the expected electrical conductivity;
- (e) determining a first heater pattern reaction extent of the first heater pattern when the estimated electrical conductivity equals the expected electrical conductivity;

(f) when the first heater pattern reaction extent is within a target coke first heater pattern reaction extent range, one of (i) heating a second heater pattern instead of the first heater pattern and (ii) modifying the heating of the first heater pattern, and

when the first heater pattern reaction extent is outside of the target coke first heater pattern reaction extent range repeating steps (a) – (e)

(g) mobilizing the hydrocarbons from at least one of the first heater pattern and the second heater pattern by heating the hydrocarbons; and

(h) producing the hydrocarbons.

3. The method of claim 2, wherein the heater comprises heaters.

4. The method of any one of claims 2-3, wherein determining the expected electrical conductivity comprises using electrical resistive tomography.

5. The method of any one of claims 2-4, wherein calculating the estimated electrical conductivity comprises determining how an experimental electrical conductivity changes as a function of an experimental coke heater pattern reaction extent and an experimental temperature.

6. The method of claim 5, wherein determining how the experimental electrical conductivity changes comprises using a functional relationship equal to:

$$\sigma = A(\epsilon_{coke})e^{B(\epsilon_{coke})T}$$

where σ is the experimental electrical conductivity, A is a first functional characteristic, ϵ_{coke} is the experimental coke heater pattern reaction extent, e is an exponential function, B is a second functional characteristic, T is the experimental temperature, $A(\epsilon_{coke})$ is that the first functional relationship is a function of the coke heater pattern reaction extent and $B(\epsilon_{coke})$ is that the second functional relationship is a function of the coke heater pattern reaction extent.

7. The method of any one of claims 5-6, wherein calculating the estimated electrical conductivity further comprises calculating a first functional characteristic and a second functional characteristic.

8. The method of claim 7, wherein calculating the first functional characteristic and the second functional characteristic comprises regressing a plot of the experimental electrical conductivity versus the experimental temperature.

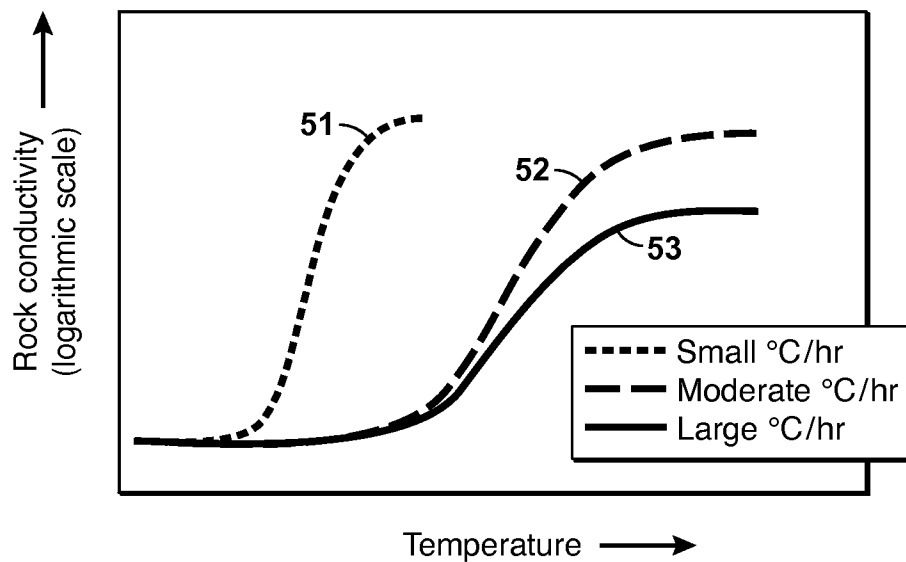
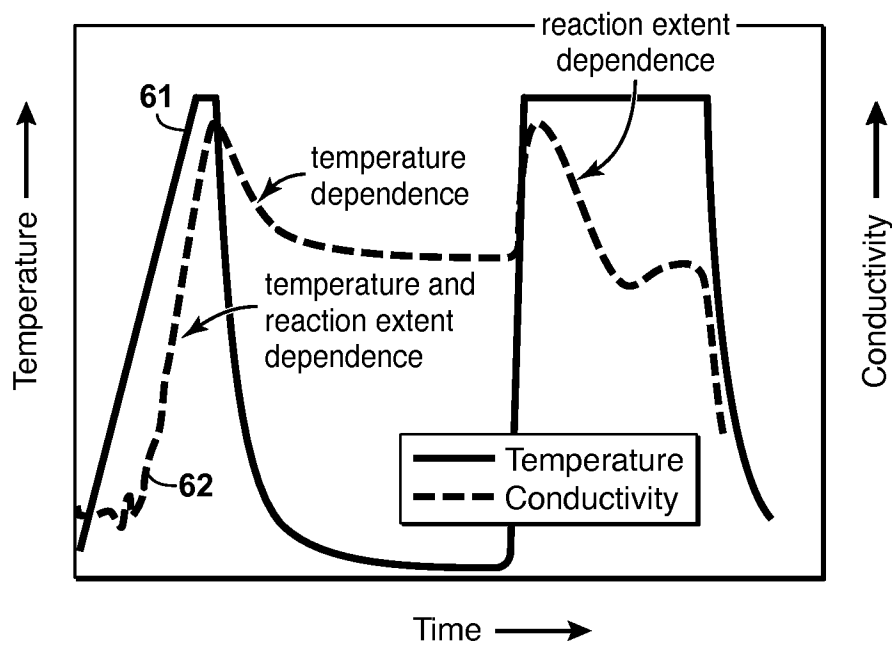
9. The method of claim any one of claims 6-8, wherein calculating the estimated electrical conductivity comprises using the functional relationship, the first functional characteristic, the second functional characteristic, and one of an estimated temperature and an estimated first heater pattern reaction extent.

11. The method of any one of claims 2-10, wherein (g) and (h) occur when (f) occurs.

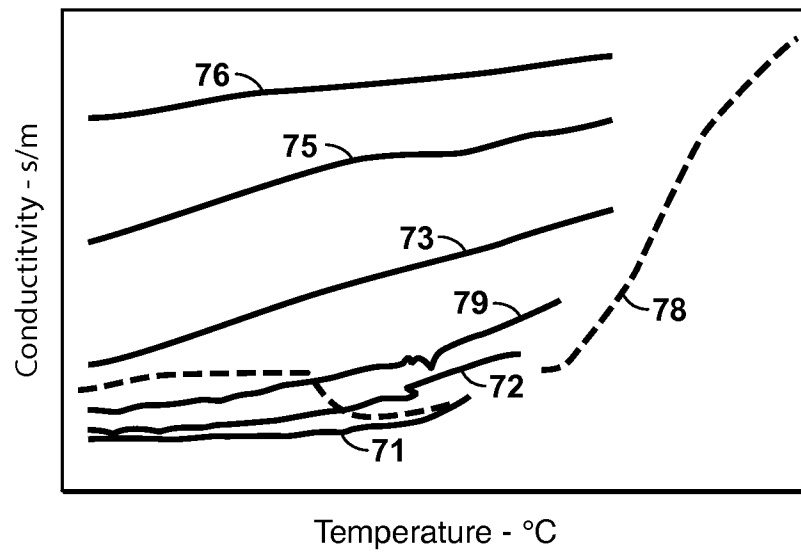
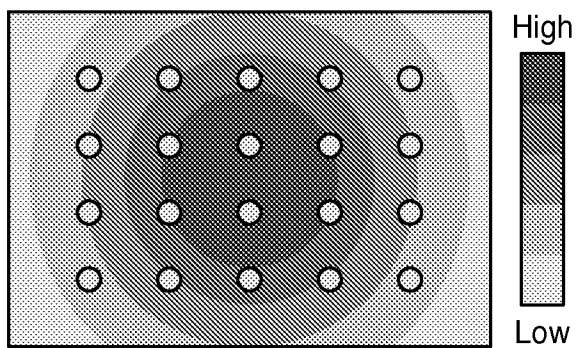
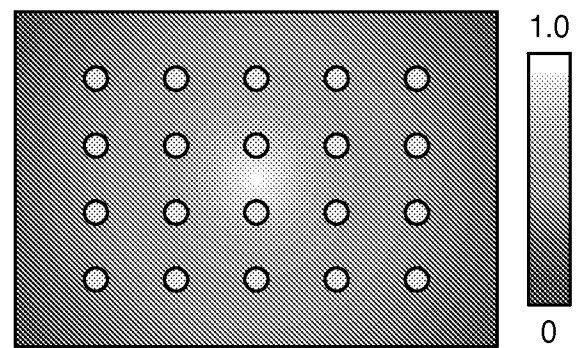
12. The method of any one of claims 2-10, wherein (g) and (h) occur after (f) occurs.

13. The method of any one of claims 2-10, wherein (g) and (h) occur when (f) occurs.

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**FIG. 1****FIG. 2**

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**FIG. 3****FIG. 4A****FIG. 4B**

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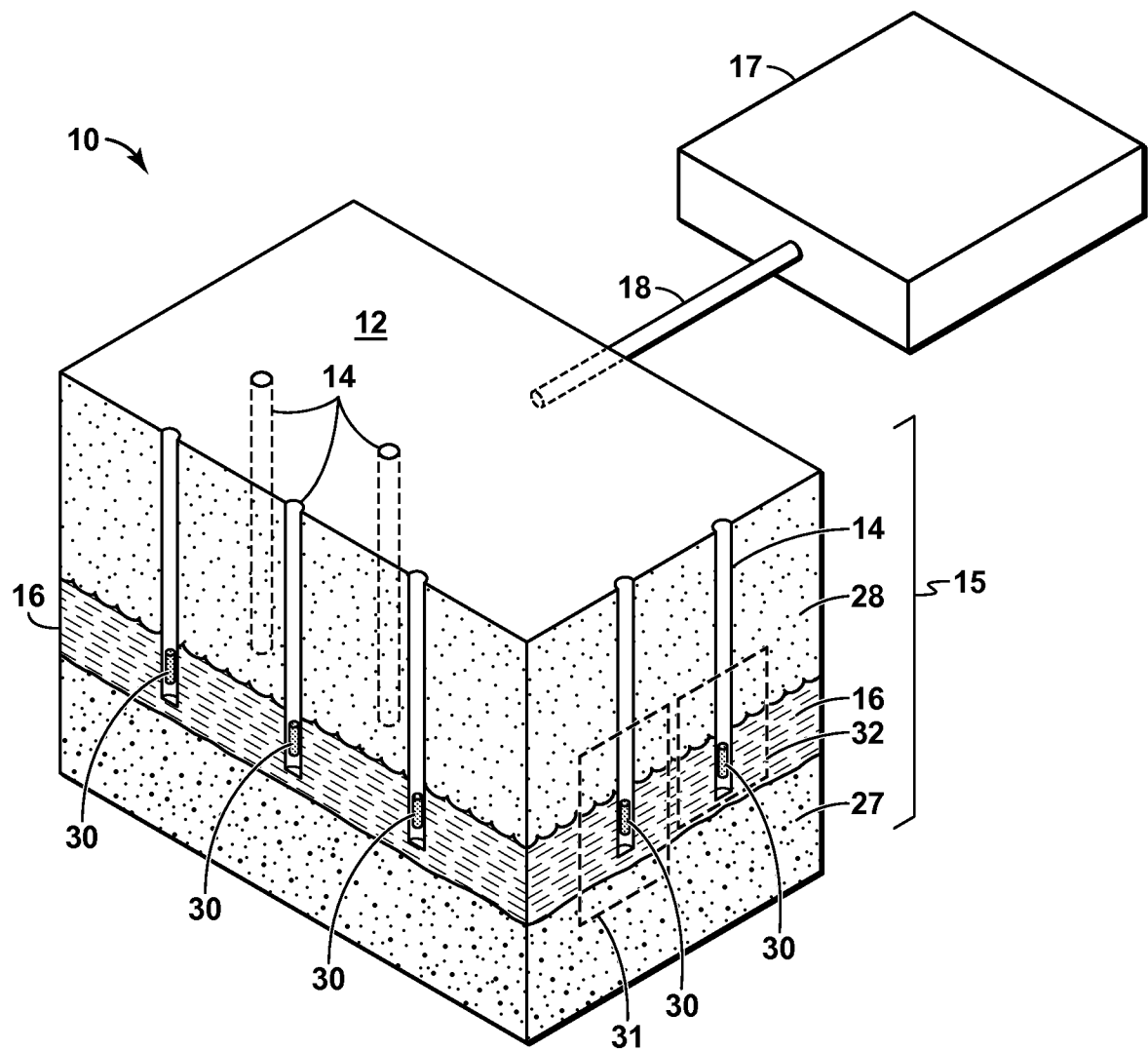
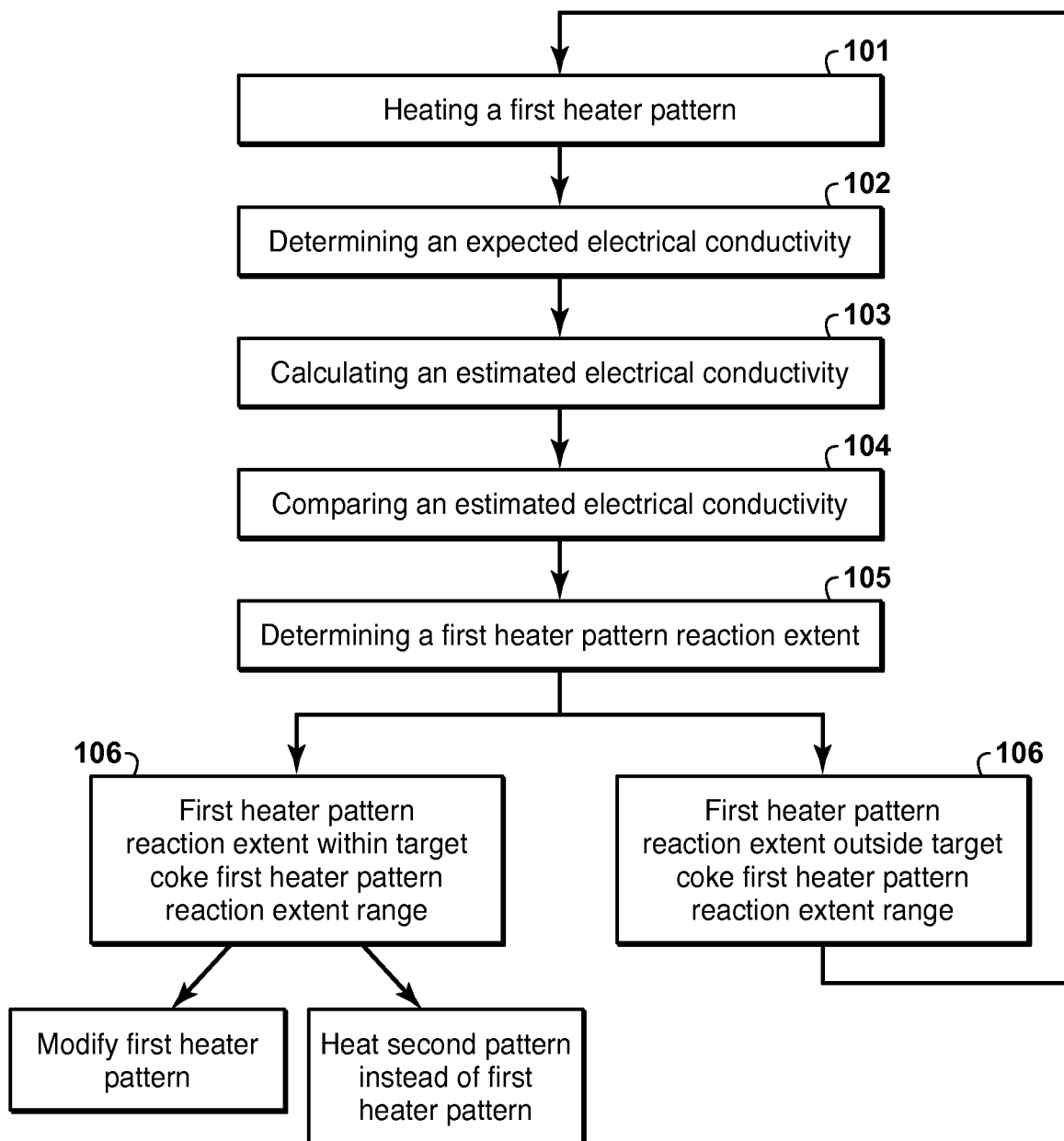


FIG. 5

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**FIG. 6**

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/028272

A. CLASSIFICATION OF SUBJECT MATTER
INV. E21B43/24 E21B43/30 E21B36/04
ADD.

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

B. FIELDS SEARCHED

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

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

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

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2012/138293 A1 (KAMINSKY ROBERT D [US] ET AL) 7 June 2012 (2012-06-07) paragraph [0019] - paragraphs [0022], [0119]; claims 1-13; figures 1-5 -----	1-13
A	US 4 415 034 A (BOUCK LARRY S [US]) 15 November 1983 (1983-11-15) abstract; claim 1; figure 1 -----	1-13
A	CN 103 244 090 A (LIAONING DONGDAIHE NEW AREA RUI SHI PETROLEUM TECHNOLOGY CO LTD) 14 August 2013 (2013-08-14) abstract; figure 1 -----	1-13



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

23 October 2015

Date of mailing of the international search report

23/11/2015

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/US2015/028272

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2012138293	A1	07-06-2012	CA 2757127 A1 03-06-2012
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