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(54) Title: BULK HEATING A SUBSURFACE FORMATION

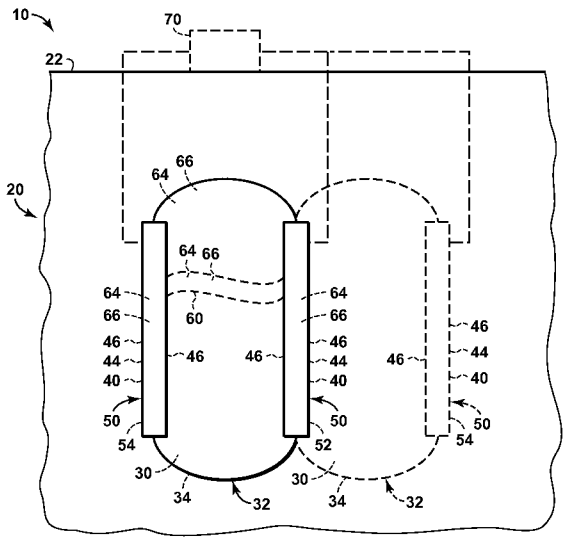


FIG. 1

(57) Abstract: Systems and methods for bulk heating of a subsurface formation with at least a pair of electrode assemblies (50) in the subsurface formation (20) are disclosed. The method may include electrically powering the pair of electrode assemblies (50) to resistively heat a subsurface region between the pair of electrode assemblies with electrical current flowing through the subsurface region between the pair of electrode assemblies; flowing a shunt mitigator (64) into at least one of the pair of electrode assemblies; and mitigating a subsurface shunt between the pair of electrode assemblies with the shunt mitigator. Mitigating may be responsive to a shunt indicator that indicates a presence of the subsurface shunt.

WO 2016/089498 A1

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BULK HEATING A SUBSURFACE FORMATION

Cross-Reference To Related Application

[0001] This application claims the benefit of U.S. Provisional Patent Application 62/087,655 filed December 4, 2014 entitled BULK HEATING A SUBSURFACE FORMATION, the entirety of which is incorporated by reference herein.

Field

[0002] The present disclosure relates to systems and methods for bulk heating a subsurface formation. More specifically, the present disclosure relates to systems and methods for mitigating subsurface shunts during bulk heating of a subsurface formation.

Background

[0003] Certain subsurface formations may include organic matter, such as shale oil, bitumen, and/or kerogen, which has material and chemical properties that may complicate production of fluid hydrocarbons from the subsurface formation. For example, the organic matter may not flow at a rate sufficient for production. Moreover, the organic matter may not include sufficient quantities of desired chemical compositions (typically smaller hydrocarbons). Hence, recovery of useful hydrocarbons from such subsurface formations may be uneconomical or impractical.

[0004] Heating of organic matter-containing subsurface formations may be particularly useful to generate producible hydrocarbons from immature organic-rich source rocks *in situ*. For example, heating organic matter-containing subsurface formations may pyrolyze kerogen into mobile liquids and gases, and may reduce the viscosity of heavy oil to enhance hydrocarbon mobility.

[0005] One method to heat a subsurface formation is to conduct electricity through the formation and, thus, resistively heat the subsurface formation. This method of heating a subsurface formation may be referred to as "bulk heating" or "volumetric heating" of the subsurface formation. Bulk heating of the subsurface formation may be accomplished by conducting electricity between electrode assemblies in the subsurface formation and through a subsurface region (volume) of naturally electrically-resistive rock between the electrode assemblies. The electrode assemblies may be contained in wellbores and/or manmade fractures, and the electrode assemblies may include electrical conductors, such as metal rods and/or granular electrically conductive materials. Bulk heating may include applying a

voltage gradient across the subsurface region to initiate a relatively uniform electrical current flow through the subsurface region. Heat may be generated within the volume of the subsurface region due to electrical resistive loss resulting from the current flow through the volume of the subsurface region (Joule heating). Bulk heating performance may not be dependent on applied thermal gradients or rock thermal conductivity – physical constraints that can impede feasibility of subsurface formation heating schemes based on thermal conduction.

[0006] As heating occurs in subsurface regions between the pairs of electrode assemblies, the electrical conductivity (or alternatively, resistivity) of the subsurface regions may change. This change in the electrical conductivity (or resistivity) of the subsurface regions may be due to physical and/or chemical changes within the subsurface regions, for example, due to temperature sensitivity of the electrical resistance of the native rock, due to native brine boiling off, due to disassociation and boil off of chemically bound water, and/or due to pyrolysis (and/or coking) of native hydrocarbons.

[0007] Heating a subsurface region via electrical conduction through the subsurface region may not occur uniformly and may suffer from instabilities, in particular if conductivity within the subsurface region increases strongly with increasing temperature. The conductivity increase within the subsurface region may result from pyrolysis occurring and may lead to the formation of electrically conductive coke or other graphitic materials. When electrical conductivity increases strongly with increasing temperature, hotter regions will become even hotter, since electricity may channel through the hotter (and more conductive) regions. Ultimately, this positive correlation between temperature and electrical conductivity may lead to the formation of a narrow, highly conductive shunt (also called a channel) between the electrode assemblies that will short-circuit the electrical flow between the electrode assemblies. Although the electrode assemblies may be large in extent or area, the bulk of the electrical flow may occur through a very small zone, and heating of the subsurface region between the electrode assemblies may be quite uneven. This phenomenon is analogous to viscous fingering that may occur when a low viscosity fluid is driven through a higher viscosity fluid. In bulk heating, the tendency for shunting instabilities to occur and the rate of shunt growth may be dependent on the heating rate and the extent to which electrical and physical property heterogeneities exist within the subsurface regions.

[0008] Conventional methods to minimize the effects of subsurface shunts during bulk heating include disconnecting at least one of the affected electrode assemblies (electrode

assemblies that conduct current into a shunted region). Disconnecting the affected electrode assembly stops the generation of heat in the shunted region, and any other (unaffected) subsurface regions, served by the affected electrode.

[0009] In view of the aforementioned disadvantages, there is a need for alternative methods and systems for bulk heating a subsurface formation. More specifically, there is a need for alternative methods and systems for mitigating the effects of subsurface shunts during bulk heating of a subsurface formation.

Summary

[0010] It is an object of the present disclosure to provide systems and methods for bulk heating of a subsurface formation. More specifically, it is an object of the present disclosure to provide systems and methods for mitigating effects of subsurface shunts during bulk heating of a subsurface formation.

[0011] A method for bulk heating a subsurface formation with at least a pair of electrode assemblies in the subsurface formation may include electrically powering the pair of electrode assemblies to resistively heat a subsurface region between the pair of electrode assemblies with electrical current flowing through the subsurface region between the pair of electrode assemblies; flowing a shunt mitigator into at least one of the pair of electrode assemblies; and, responsive to a shunt indicator, mitigating a subsurface shunt between the pair of electrode assemblies with the shunt mitigator, wherein the shunt indicator indicates a presence of the subsurface shunt.

[0012] A method for bulk heating a subsurface formation with at least a pair of electrode assemblies in the subsurface formation may include electrically powering the pair of electrode assemblies to resistively heat an *in situ* resistive heater, wherein the *in situ* resistive heater is a subsurface region of the subsurface formation between the pair of electrode assemblies; upon determining a presence of a subsurface shunt between the pair of electrode assemblies, forming a modified *in situ* resistive heater by mitigating the subsurface shunt; and electrically powering the pair of electrode assemblies to resistively heat the modified *in situ* resistive heater.

[0013] A subsurface formation may include at least a pair of electrode assemblies, wherein each electrode assembly of the pair of electrode assemblies may include an electrically conductive material, and wherein at least one electrode assembly of the pair of

electrode assemblies may include a shunt mitigator that is selected to undergo a state change in response to a shunt indicator.

[0014] 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.

Description of the Drawings

[0015] These and other features, aspects and advantages of the present disclosure will become apparent from the following description and the accompanying drawings, which are briefly discussed below.

[0016] Fig. 1 is a schematic representation of electrode assemblies in a subsurface formation.

[0017] Fig. 2 is a schematic representation of bulk heating methods to mitigate subsurface shunt formation.

[0018] Fig. 3 is a schematic representation of the system of Fig. 1 during the application of a shunt mitigator.

[0019] Fig. 4 is a schematic representation of the system of Fig. 3 after the subsurface shunt is mitigated.

[0020] Fig. 5 is a schematic representation of bulk heating methods that are responsive to subsurface shunt formation.

[0021] It should be noted that the figures are merely examples and no limitations on the scope of the present disclosure are intended thereby. Further, the figures are generally not drawn to scale, but are drafted for purposes of convenience and clarity in illustrating various aspects of the disclosure.

Detailed Description

[0022] 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 not relevant to the present disclosure may not be shown in the drawings for the sake of clarity.

[0023] At the outset, for ease of reference, certain terms used in this application and their meanings 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.

[0024] 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.

[0025] "Heavy oil" includes oils which are classified by the American Petroleum Institute ("API"), as heavy oils, extra heavy oils, or bitumens. The term "heavy oil" includes bitumen. Heavy oil may have a viscosity of about 1,000 centipoise (cP) or more, 10,000 cP or more, 100,000 cP or more, or 1,000,000 cP or more. In general, a heavy oil has an API gravity between 22.3° API (density of 920 kilograms per meter cubed (kg/m^3) or 0.920 grams per centimeter cubed (g/cm^3)) and 10.0° API (density of 1,000 kg/m^3 or 1 g/cm^3). An extra heavy oil, in general, has an API gravity of less than 10.0° API (density greater than 1,000 kg/m^3 or 1 g/cm^3). For example, a source of heavy oil includes oil sand or bituminous sand, which is a combination of clay, sand, water and bitumen. The recovery of heavy oils is based on the viscosity decrease of fluids with increasing temperature or solvent concentration. Once the viscosity is reduced, the mobilization of fluid by steam, hot water flooding, or gravity is possible. The reduced viscosity makes the drainage or dissolution quicker and therefore directly contributes to the recovery rate.

[0026] 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.

[0027] 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.

[0028] 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).

[0029] As used herein, the term "kerogen" refers to a solid, insoluble hydrocarbon that may principally contain carbon, hydrogen, nitrogen, oxygen, and/or sulfur.

[0030] As used herein, the term "oil" refers to a hydrocarbon fluid containing primarily a mixture of condensable hydrocarbons.

[0031] 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.

[0032] 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, silicilytes, carbonates, and diatomites. Organic-rich rock may contain kerogen.

[0033] 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, oil sands formations or other formation hydrocarbons.

[0034] As used herein, "overburden" refers to the material overlying a subsurface (subterranean) reservoir. The overburden may include rock, soil, sandstone, shale, mudstone, carbonate and/or ecosystem above the subsurface 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.

[0035] As used herein, the term "pyrolysis" 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.

[0036] As used herein, "reservoir," "subsurface 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).

[0037] 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.

[0038] As used herein "subsurface 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.

[0039] As used herein, "underburden" refers to the material underlaying a subterranean reservoir. The underburden may include rock, soil, sandstone, shale, mudstone, wet/tight carbonate and/or ecosystem below the subterranean reservoir.

[0040] 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.

[0041] The terms "approximately," "about," "substantially," and similar terms are intended to have a broad meaning in harmony with the common and accepted usage by those of ordinary skill in the art to which the subject matter of this disclosure pertains. It should be understood by those of skill in the art who review this disclosure that these terms are intended to allow a description of certain features described and claimed without restricting the scope of these features to the precise numeral ranges provided. Accordingly, these terms should be

interpreted as indicating that insubstantial or inconsequential modifications or alterations of the subject matter described and are considered to be within the scope of the disclosure.

[0042] 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.

[0043] "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.

[0044] Where two or more ranges are used, such as but not limited to 1 to 5 or 2 to 4, any number between or inclusive of these ranges is implied.

[0045] As used herein, the phrase, "for example," the phrase, "as an example," and/or simply the term "example," when used with reference to one or more components, features, details, structures, and/or methods according to the present disclosure, are intended to convey that the described component, feature, detail, structure, and/or method is an illustrative, non-exclusive example of components, features, details, structures, and/or methods according to the present disclosure. Thus, the described component, feature, detail, structure, and/or method is not intended to be limiting, required, or exclusive/exhaustive; and other components, features, details, structures, and/or methods, including structurally and/or

functionally similar and/or equivalent components, features, details, structures, and/or methods, are also within the scope of the present disclosure.

[0046] As used herein, the terms "adapted" and "configured" mean that the element, component, or other subject matter is designed and/or intended to perform a given function. Thus, the use of the terms "adapted" and "configured" should not be construed to mean that a given element, component, or other subject matter is simply "capable of" performing a given function but that the element, component, and/or other subject matter is specifically selected, created, implemented, utilized, programmed, and/or designed for the purpose of performing the function. It is also within the scope of the present disclosure that elements, components, and/or other recited subject matter that is recited as being adapted to perform a particular function may additionally or alternatively be described as being configured to perform that function, and vice versa. Similarly, subject matter that is recited as being configured to perform a particular function may additionally or alternatively be described as being operative to perform that function.

[0047] Figs. 1-5 provide examples of systems and methods for bulk heating of a subsurface formation. More specifically, Figures 1-5 provide examples of systems and methods for mitigating subsurface shunts during bulk heating of a subsurface formation. Elements that serve a similar, or at least substantially similar, purpose are labeled with numbers consistent among the figures. The corresponding elements with like numbers in each of the figures may not be discussed in detail herein with reference to each of the figures. Similarly, all elements may not be labeled in each of the figures, but associated reference numerals may be utilized for consistency. Elements, components, and/or features that are discussed with reference to one or more of the figures may be included in and/or utilized with any of the figures without departing from the scope of the present disclosure.

[0048] In general, elements that are likely to be included are illustrated in solid lines, while elements that are optional are illustrated in dashed lines. However, elements that are shown in solid lines may not be essential. Thus, an element shown in solid lines may be omitted without departing from the scope of the present disclosure.

[0049] Fig. 1 is a schematic representation of a bulk heating system 10. Bulk heating systems 10 may include at least two electrode assemblies 50 that extend into a subsurface formation 20. The at least two electrode assemblies 50 may form, or define, at least a pair of electrode assemblies 50. More specifically, electrode assemblies 50 are in electrical communication with a subsurface formation 20, and the electrode assemblies are configured

in adjacent pairs to form electrical circuits with a subsurface region 32 between each pair of electrode assemblies 50. Individual electrode assemblies 50 may be a member of more than one pair of electrode assemblies 50 and may be in electrical communication with more than one subsurface region 32. For clarity, Fig. 1 illustrates in solid lines two spaced-apart electrode assemblies 50. As schematically illustrated with dashed lines, bulk heating systems 10 may include more than two electrode assemblies 50, for example, 3, 4, 5, 6, or more than 6 electrode assemblies 50.

[0050] Subsurface formation 20 is a finite subsurface (subterranean) region. Subsurface formation 20 may be of any geologic form and may contain one or more organic matter-containing regions (e.g., layers, intervals, etc.), one or more regions with little to no organic matter, an overburden, and/or an underburden. Subsurface formation 20 may be below an overburden and/or above an underburden. In Fig. 1, subsurface formation 20 is schematically indicated to include organic matter 30 (e.g., a solid, liquid, and/or gaseous hydrocarbon mineral such as hydrocarbon compounds, shale oil, bitumen, bituminous coal, and/or kerogen). Subsurface formation 20 may be at least 100 m, at least 200 m, at least 500 m, at least 1,000 m, at least 2,000 m, at least 5,000 m, at most 20,000 m, at most 10,000 m, at most 5,000 m, at most 2,000 m, at most 1,000 m, and/or at most 500 m below the Earth's surface 22. Suitable depth ranges may include combinations of any upper and lower depth listed above or any number within or bounded by the preceding depth ranges.

[0051] Subsurface regions 32 may be portions of the subsurface formation 20 that are in electrical contact with at least two electrode assemblies 50, i.e., subsurface regions 32 adjoin at least two adjacent electrode assemblies 50. Subsurface regions 32 generally may extend between at least a pair of electrode assemblies 50.

[0052] Subsurface regions 32 may be the regions of subsurface formation 20 that are heated by the bulk heating system 10 via electrical resistive heating (Joule heating). Subsurface regions 32 may be electrically powered (also called energized) to cause resistive heating, i.e., electrical power dissipated within a given subsurface region 32 may heat the given subsurface region 32. Electrically powering (also referred to as transmitting electricity) may be the result of connecting different voltages to different electrode assemblies 50 and applying the voltages to cause current to flow through the subsurface region 32 between the electrode assemblies 50. When electrically powered and resistively heating, subsurface regions 32 may be referred to as *in situ* resistive heaters 34. The heating and/or the power dissipated within the subsurface regions 32 may be expressed as power deposited and/or

dissipated per volume (or length cubed). For illustration purposes, *in situ* resistive heaters 34 are depicted schematically via example electrical flow lines between adjacent electrode assemblies 50. It should be understood that electricity flow is occurring over the entire exposed surface of an electrode assembly 50 and not just where flow lines are shown.

[0053] Electrode assemblies 50 may include at least one wellbore 40 and/or fracture 44. Electrode assemblies 50 may include electrically conductive material sufficient to conduct electricity from the surface 22 to the adjoining subsurface region(s) 32 without undue power loss (due to electrical resistive heating). An electrode assembly 50 may be electrically connected to one or more subsurface regions 32 of the subsurface formation 20 that adjoin the electrode assembly 50. An electrode assembly 50 may include a wellbore 40 that includes an electrically conductive wire, cable, casing, tubular, rod, etc., and that is electrically connected to at least one subsurface region 32 adjoining the wellbore 40. An electrode assembly 50 may include a fracture 44 that includes conductive media, such as electrically conductive particulate and/or electrically conductive fluid.

[0054] Wellbores 40 may be substantially vertical, substantially horizontal, any angle between vertical and horizontal, deviated or non-deviated, and combinations thereof, for example, a vertical well with a non-vertical segment. As used herein, "substantially vertical" means within 15° of true vertical and "substantially horizontal" means within 15° of true horizontal. Wellbores 40 may include and/or may be supported, lined, sealed, and/or filled with materials such as casings, linings, sheaths, conduits, electrically conductive materials (e.g., metal rods, metal cables, metal wires, metal tubulars, electrically conductive particulate, electrically conductive granular materials, and/or electrically conductive liquid). Wellbores 40 may be configured to be in electrical and/or fluidic communication with the subsurface formation 20 and/or one or more subsurface regions 32.

[0055] Fractures 44 may be natural and/or manmade cracks, or surfaces of breakages, within rock in the subsurface formation 20. Fractures 44 may be induced mechanically in subsurface regions, for example, by hydraulic fracturing (in which case, the fracture 44 may be referred to as a hydraulic fracture). Another example of a method of forming of fractures 44 is steam fracturing (in which case, the fracture 44 may be referred to as a steam fracture). Fractures 44 may be referred to as hydraulic fractures and steam fractures, respectively. Fractures 44 may be substantially planar. Fractures 44 may be substantially vertical, substantially horizontal, any angle between vertical and horizontal, branched, networked, and combinations thereof, for example, a planar vertical fracture with a non-vertical branch. The

length of a fracture 44 may be a distance from the source of the fracture (e.g., a wellbore 40 used to establish the fracture) to a fracture tip (the furthest point of the fracture from the source) or the distance along the fracture between the two farthest spaced fracture tips. Fractures 44 may be configured to be in electrical and/or fluidic communication with the subsurface formation 20 and/or one or more subsurface regions 32. For illustration purposes, the widths of the fractures 44 are exaggerated compared to the length of the fractures. For example, fracture widths may be on order of a few millimeters or centimeters, whereas fracture lengths may be on order of tens or hundreds of meters.

[0056] Fractures 44 may be held open with granular material called proppant. Fractures 44 may include and/or may be supported, lined, sealed, and/or filled with other materials, such as electrically conductive materials, particulate, granular materials, liquids, and/or gases. Proppant may be electrically conductive. Electrically conductive materials may include at least one of granular material, granules, particles, filaments, metal, granular metal, metal coated particles, coke, graphite, electrically conductive gel, and electrically conductive liquid. For example, the proppant may include, and/or may be, graphite particles. As other examples, the proppant may include, and/or may be, an electrically conductive material, such as metal particles, metal coated particles, and/or coke particles.

[0057] Electrode assemblies 50 may be arranged in pairs of adjacent electrode assemblies 50 within the subsurface formation. The pair of electrode assemblies 50 in each pair of adjacent electrode assemblies 50 may be nearer to each other than to other, non-adjacent electrode assemblies 50. Relative to a given electrode assembly 50, an adjacent electrode assembly 50 may be the closest electrode assembly 50 or one of the closest electrode assemblies 50. Pairs of adjacent electrode assemblies 50 are not necessarily within a small distance of each other and may be separated by distances of hundreds of meters. The distance between electrode assemblies 50 is the shortest distance between the electrode assemblies 50 through the subsurface region 32 that separates the electrode assemblies 50. Electrode assemblies 50 may be deemed adjacent when no other electrode assembly 50 intersects a line spanning the shortest distance between the electrode assemblies 50.

[0058] Electrode assemblies 50 may be arranged in pairs, groups, rows, columns, and/or arrays. The electrode assemblies 50 may be spaced apart and may have a substantially uniform spacing (at least in one direction). For example, electrode assemblies may be spaced apart with a spacing of at least 5 m, at least 10 m, at least 20 m, at least 50 m, at least 100 m, at least 200 m, at most 500 m, at most 200 m, at most 100 m, at most 50 m, and/or at most

20 m. Groups, rows, columns, and arrays of electrode assemblies 50 may include inside electrode assemblies 52 and outer electrode assemblies 54. Outer electrode assemblies 54 may be adjacent and/or connected to fewer electrode assemblies 50 than inside electrode assemblies 52. For example, rows and columns of electrode assemblies 50 may include a first outer electrode assembly 54 at one end of the row or column and a second outer electrode assembly 54 at the other end of the row or column. The first outer electrode assembly 54 may be adjacent to only one electrode assembly 50; the second outer electrode assembly 54 may be adjacent to only one electrode assembly 50; and the inside electrode assemblies 52 may each be adjacent to two electrode assemblies 50 of the electrode assemblies in the row or column. The inside electrode assemblies 52 may be referred to as middle electrode assemblies 52, central electrode assemblies 52, intermediate electrode assemblies 52, inner electrode assemblies 52, and/or interior electrode assemblies 52. The outer electrode assemblies 54 may be referred to as edge electrode assemblies 54 and/or end electrode assemblies 54.

[0059] Electrode assemblies 50 may be oriented with respect to each other. For example, two or more electrode assemblies 50 (or portions thereof) may be at least substantially parallel to each other and substantially facing each other. In particular, two electrode assemblies 50 may each include a generally planar fracture 44, and the fractures 44 of the electrode assemblies 50 may be substantially parallel to each other, with each electrode assembly 50 including a face, or generally planar fracture surface, 46 that faces a corresponding face 46 of the other electrode assembly 50. In the example of Fig. 1, two substantially parallel fractures 44 (shown in solid lines) each form a portion of two separate electrode assemblies 50. The two solid-line electrode assemblies 50 illustrated in Fig. 1 may be deemed parallel electrode assemblies 50.

[0060] Adjacent electrode assemblies 50 may be configured to transmit electricity and/or to electrically power the subsurface region(s) 32 between the adjacent electrode assemblies 50. The electrode assemblies 50 may be configured to apply a voltage across and/or to supply an electrical current through the corresponding subsurface region(s) 32. Electrical power supplied to the subsurface region(s) 32 may be DC (direct current) power and/or AC (alternating current) power. The electrical power may be supplied by an electrical power source 70. As indicated in Fig. 1, electrical power source 70 may be electrically connected to the electrode assemblies 50 from a surface (above-ground) location 22.

[0061] DC power may be supplied by applying a voltage difference (gradient) across the subsurface region 32. In a DC powered configuration, one of the electrode assemblies 50 contacting the subsurface region 32 may have a higher voltage (called the high voltage and/or the high polarity), and another electrode assembly 50 contacting the subsurface region 32 may have a lower voltage (called the low voltage and/or the low polarity). If the high polarity is a positive voltage and the low polarity is a negative voltage, the high polarity and the low polarity may be referred to as the positive polarity and the negative polarity, respectively. Where DC power is supplied, the voltages of the electrode assemblies 50 may be occasionally (e.g., periodically) switched, for example, to avoid electrochemical effects and electrode degradation at the electrode assemblies 50.

[0062] AC power may be supplied by applying different voltage waveforms (also called alternating voltages) to different electrode assemblies 50 in contact with the same subsurface region 32. Generally, the applied alternating voltages are periodic, have the same frequency, and have differing phase angles. Suitable AC frequencies include at least 10 Hz (hertz), at least 30 Hz, about 50 Hz, about 60 Hz, about 100 Hz, about 120 Hz, at least 100 Hz, at least 200 Hz, at least 1,000 Hz, at least 10,000 Hz, at most 100,000 Hz, at most 300,000 Hz, at most 1,000,000 Hz, at most 5,000,000 Hz, and/or at most 15,000,000 Hz. Suitable ranges may include combinations of any upper and lower AC frequency listed above or any number within or bounded by the AC frequencies listed above. The AC frequency may be selected to be below a frequency at which radio-frequency (dielectric) heating dominates over resistive (Joule) heating of the subsurface formation 20.

[0063] AC power may be supplied as one or more alternating voltages, and each electrode assembly 50 may have an alternating voltage or a DC voltage applied. For example, AC power may be supplied in a single-phase configuration where an alternating voltage is applied to one electrode assembly 50 and a DC voltage (also referred to as a neutral voltage) is applied to another electrode assembly 50. As other examples, AC power may be supplied in a two-phase configuration, a three-phase configuration, and/or in a multi-phase configuration. The 'electrical phases' available in a multi-phase configuration are alternating voltages having the same frequency and different phase angles (i.e., nonequal phase angles). Generally, the phase angles are relatively evenly distributed within the period of the AC power (the period is the inverse of the shared frequency of the alternating voltages). For example, common phase angles for a two-phase configuration are 0° and 180° (a phase angle difference of ±180°, i.e., of 180° in absolute value), and 0° and 120° (for example, two of the

three poles from a 3-phase generator). Common phase angles for a three-phase configuration are 0°, 120°, and 240° (phase angle differences of ±120°, i.e., of 120° in absolute value). Though less common, other multi-phase configurations (e.g., 4, 5, 6, or more 'electrical phases') and/or other phase angles, and other phase angle differences, may be utilized to supply AC power.

[0064] When electrical power is supplied to subsurface regions 32, the subsurface regions 32 may resistively heat and become more electrically conductive. As the subsurface regions 32 are heated, the electrical conductivity may increase (and the electrical resistivity may decrease) due to physical and/or chemical changes within the subsurface regions 32, for example, due to temperature sensitivity of the electrical resistance of the native rock, due to native brine boiling off, and/or due to pyrolysis (and/or coking) of native organic matter and/or native hydrocarbons. Before heating, the subsurface regions 32 may be relatively poorly electrically conductive, for example, having an average electrical conductivity of less than 1 S/m (Siemens/meter), less than 0.1 S/m, less than 0.01 S/m, less than 0.001 S/m, less than 10^{-4} S/m, less than 10^{-5} S/m, less than 10^{-6} S/m, less than 10^{-7} S/m, and/or within a range that includes or is bounded by any of the preceding examples of average electrical conductivity. Upon heating, the subsurface regions 32 may become more electrically conductive, achieving an average electrical conductivity of at least 10^{-5} S/m, at least 10^{-4} S/m, at least 10^{-3} S/m, at least 0.01 S/m, at least 0.1 S/m, at least 1 S/m, at least 10 S/m, at least 100 S/m, at least 1,000 S/m, and/or within a range that includes or is bounded by any of the preceding examples of average electrical conductivity.

[0065] Where electrical conduction and/or resistive heating is not uniform within subsurface region 32, a subsurface shunt may form between electrode assemblies 50 that serve the subsurface region 32. An example of such a subsurface shunt is schematically illustrated in Fig. 1 at 60. The subsurface shunt 60 may form because electrical conductivity increases with increasing temperature and/or may form due to inhomogeneities (such as electrically-conductive and/or fluidically-conductive regions) within the subsurface region 32. The subsurface shunt 60 may be a region, a pathway, and/or a channel that extends between two electrode assemblies 50 within the subsurface region 32, and which has a higher electrical conductivity than the rest of the subsurface region 32. Subsurface shunts 60 may be electrical shorts between electrode assemblies 50. Subsurface shunts 60 may divert electrical current supplied by the electrode assemblies 50 away from the bulk of the subsurface regions 32 and into the subsurface shunts 60. Subsurface shunts 60 may be, and/or may include, a

fluid path between electrode assemblies 50. Subsurface shunts 60 may transmit fluid injected into one electrode assembly 50 to another, connected, electrode assembly 50.

[0066] When subsurface shunts 60 become sufficiently electrically conductive, the majority of electrical current passing between the electrode assemblies 50 may travel through the subsurface shunts 60. The positive correlation between temperature and electrical conductivity may reinforce and/or concentrate the subsurface shunts 60 as electrical current flows through the subsurface shunts 60. Subsurface shunts 60 may be very small as compared to the corresponding subsurface regions 32. The electrical current and the consequent heating may be very highly concentrated within the subsurface shunts 60.

[0067] The average electrical conductivity of subsurface shunts 60 may be at least 10^{-5} S/m, at least 10^{-4} S/m, at least 10^{-3} S/m, at least 0.01 S/m, at least 0.1 S/m, at least 1 S/m, at least 10 S/m, at least 100 S/m, at least 300 S/m, at least 1,000 S/m, at least 3,000 S/m, at least 10,000 S/m, and/or within a range that includes or is bounded by any of the preceding examples of average electrical conductivity. The electrical conductivity of the subsurface shunt 60 may be so great, relative to the remainder of the subsurface region 32, that the average electrical conductivity of the subsurface region 32 may be dominated by the average electrical conductivity of the included subsurface shunt 60.

[0068] The presence of a subsurface shunt 60 within the subsurface region 32 may increase the electrical power flowing through the subsurface region 32 and/or through the localized region corresponding to the subsurface shunt 60. The increased electrical power flowing through the subsurface shunt 60 may increase resistive heating within the subsurface shunt 60 and/or may decrease electrical power flowing and/or resistive heating outside of the subsurface shunt 60. The presence of a subsurface shunt 60 within the subsurface region 32 may be indicated by one or more thermal, mechanical, and/or electrical parameters (referred to as shunt indicators) relating to the bulk heating system 10, the subsurface region 32, one or more of the electrode assemblies 50, and/or the subsurface shunt 60 (at least the region of the subsurface region 32 corresponding to the subsurface shunt). Shunt indicators may be the value of, and/or changes in, one or more thermal parameters, mechanical parameters, electrical parameters, and/or related quantities. Thermal parameters may include the average temperature, a point (localized) temperature, a temperature difference, and/or a temperature gradient (temperature difference per length). Mechanical parameters may include fluid permeability and/or porosity. Electrical parameters may be electrical conductivity-related parameters, which may include, and/or may be, at least one of conductivity (a material's

intrinsic ability to conduct electrical current), conductance (the ease with which electrical current may flow through an object or defined region), resistivity (a material's intrinsic ability to oppose electrical current flow), resistance (the opposition to the flow of electrical current through an object or defined region), current (electrical current flow), voltage (electrical potential), and/or a density and/or gradient of any of the preceding examples of electrical conductivity-related parameters.

[0069] Electrical conductivity may be referred to as specific electrical conductance and/or volume conductivity. Electrical resistivity may be referred to as specific electrical resistance and/or volume resistivity. Electrical conductivity, conductance, resistivity, and resistance each may be an AC and/or a DC quantity, i.e., each may be described as a complex quantity, a magnitude, a phase angle, and/or a frequency-dependent quantity. When specifically referring to AC quantities, electrical conductivity may be called electrical admittivity and/or a real part of the complex electrical admittivity, electrical conductance may be called electrical admittance and/or a real part of the complex electrical admittance, electrical resistivity may be called electrical impeditivity and/or a real part of the complex electrical impeditivity, and electrical resistance may be called electrical impedance and/or a real part of the complex electrical impedance.

[0070] Bulk heating systems 10 may include a shunt mitigator 64 in and/or near the electrode assemblies 50, the subsurface region 32, and/or the subsurface shunt 60. The shunt mitigator 64 may be a material configured to selectively attenuate and/or eliminate electrical current flow through the subsurface shunt 60 in response to and/or in the presence of the subsurface shunt 60. The shunt mitigator 64 may be, optionally selectively, located and/or placed in the electrode assemblies 50, the subsurface region 32, and/or the subsurface shunt 60 to attenuate and/or eliminate electrical current flow through the subsurface shunt 60. The shunt mitigator 64 may be, optionally selectively, located and/or placed before, during, and/or after the electrode assemblies 50 are formed. The shunt mitigator 64 may be, optionally selectively, located and/or placed before, during, and/or after the subsurface shunt 60 is formed.

[0071] The shunt mitigator 64 may be a solid (e.g., particles, granules, etc.), a liquid, a gas, and/or a combination of solid, liquid, and/or gas. The shunt mitigator 64 may be placed in (e.g., into porous regions within) the electrode assemblies 50, the subsurface region 32, and/or the subsurface shunt 60 by flowing and/or injection under pressure. Where the shunt mitigator includes solids, the solids may be suspended and/or dispersed in a carrier fluid.

[0072] Shunt mitigator 64 may be within the electrode assemblies 50. For example, a solid and/or liquid shunt mitigator may be electrically conductive and may be at least a portion of the electrical conductive material that forms an electrically conductive path from the surface 22 to the subsurface region 32. Whether electrically conductive or not, the solid and/or liquid shunt mitigator 64 may be flowed into the wellbore 40 and/or the fracture 44 of the electrode assembly 50 with (other) electrically conductive materials (e.g., during formation of the electrode assembly 50). When electrically conductive, the solid and/or liquid shunt mitigator 64 may be flowed into the wellbore 40 and/or the fracture 44 as the electrically conductive material of the electrode assembly 50. The solid and/or liquid shunt mitigator 64 may be flowed into electrode assembly 50 after the electrode assembly 50 already includes electrically conductive material.

[0073] Shunt mitigators 64 that are solid may be granular and may be at least a portion of the proppant that holds open a fracture 44 of the electrode assembly. For example, shunt mitigator 64 may be flowed with, and/or as, proppant into a fracture 44 during formation and/or propping of the fracture 44.

[0074] As shunt mitigators 64 that are fluid (e.g., liquid and/or gaseous) may tend to not be retained within a selected location within the electrode assemblies 50, the subsurface region 32, and/or the subsurface shunt 60, fluid shunt mitigators 64 may be flowed into at least one electrode assembly 50 in anticipation of, during, and/or after formation of a subsurface shunt 60.

[0075] The shunt mitigator 64 may be configured to change one or more properties of the shunt mitigator in response to the presence of a subsurface shunt 60 (e.g., in response to a shunt indicator). The shunt mitigator 64 may be configured such that the change in its properties results in a decrease in the electrical conductance (i.e., an increase in the electrical resistance) of the subsurface shunt 60 and/or a decrease in the electrical current flowing through the subsurface shunt 60. The shunt mitigator 64 may be configured such that the change in its properties results in a decrease in the electrical conductivity (i.e., an increase in the electrical resistivity) of the subsurface shunt 60 and/or at least a portion of at least one of the electrode assemblies 50 near the subsurface shunt 60. The properties may include at least one of electrical conductivity, electrical admittivity, electrical resistivity, electrical impeditivity, electric susceptibility, electric permittivity, magnetic susceptibility, magnetic permeability, density, viscosity, volume, and chemical activity.

[0076] The shunt mitigator 64 may be configured to decrease its electrical conductivity (i.e., to increase electrical resistivity) in response to the shunt indicator. For example, the shunt mitigator 64 may decrease its electrical conductivity in response to temperatures above a predetermined threshold. If electrically powered by a voltage-limited power source, an increase in temperature, which may be due to a subsurface shunt 60, may result in a decrease in electrical power dissipated in the shunt mitigator 64 and consequently less heating due to electricity flowing through the shunt mitigator 64. In response to the shunt indicator, the shunt mitigator 64 may be configured to decrease its electrical conductivity at one or more frequencies, and/or above or below a cutoff frequency.

[0077] The shunt mitigator 64 may be configured to chemically react, in response to the shunt indicator, with at least one of the subsurface region 32, the subsurface shunt 60, and one or more of the electrode assemblies 50. As an example, the shunt mitigator 64 may include, may include a source of, and/or may be molecular oxygen, carbon dioxide, an oxidizing gas, and/or a gasification gas. These examples of shunt mitigators 64 may selectively react with (selectively oxidize) electrically-conductive carbon (e.g., residual char or a source of elemental carbon) in the subsurface shunt 60, for example, because the shunt mitigator 64 is selectively placed in the subsurface shunt, and/or because electrically-conductive carbon is relatively more prevalent in the subsurface shunt 60 than in the electrode assemblies 50. A gasification gas is a gas that, when added to electrically-conductive carbon under appropriate conditions, reacts to form a gaseous carbon compound (such as carbon monoxide). A gasification gas may be carbon dioxide or a gas that may be decomposed into a carbon dioxide product. When electrically-conductive carbon is oxidized, the amount of electrically-conductive carbon may be reduced and/or the electrically-conductive carbon may be transformed into other carbon-containing compounds that are less electrically-conductive (e.g., carbon monoxide). Hence, oxidization of electrically-conductive carbon within and/or near the subsurface shunt 60 may reduce the electrical conductance, i.e., increase the electrical resistance, of the subsurface shunt 60.

[0078] The shunt mitigator 64 may be configured to decompose in response to the shunt indicator, to polymerize in response to the shunt indicator, and/or to melt in response to the shunt indicator. For example, the shunt mitigator 64 may include, and/or may be, a carbonate mineral such as calcite and/or dolomite. Carbonate minerals may decompose at elevated temperatures that may be generated within the subsurface region 32 and/or the subsurface shunt 60. For example, dolomite may decompose at about 550°C, and calcite may

decompose at about 700°C. Decomposition of carbonate minerals may result in the production of carbon dioxide gas, which may oxidize electrically conductive carbon in the subsurface shunt 60 and/or in a region near the subsurface shunt 60. As discussed, oxidization of electrically conductive carbon within and/or near the subsurface shunt 60 may reduce the electrical conductance of the subsurface shunt 60. The shunt mitigator 64 may be electrically conductive and form at least a portion of the electrically conductive path of an electrode assembly. When the shunt mitigator 64 decomposes, the shunt mitigator may become less electrically conductive and/or may transform into a mobile material (e.g., a liquid and/or a gas) that migrates away from the site of decomposition. Such decomposition may leave a void and/or a region of higher electrical resistance in the electrical path to the subsurface shunt 60 and thereby reduce the electrical conductance through the subsurface shunt 60.

[0079] The shunt mitigator 64 may be configured to change volume and/or density in response to the shunt indicator. For example, the shunt mitigator 64 may be electrically insulating and intermixed within the electrically conductive material that forms the electrical path through an electrode assembly to the subsurface region 32. When the subsurface shunt 60 forms, the shunt mitigator 64 near the subsurface shunt 60 may expand and displace electrically conductive material near the subsurface shunt 60 and thereby reduce the electrical conductance through the subsurface shunt 60.

[0080] The shunt mitigator 64 may be configured to undergo a state change in response to the presence of the subsurface shunt 60 (e.g., in response to a shunt indicator). The state change is a change in property of the shunt mitigator 64. The shunt mitigator 64 may be configured such that the state change results in a decrease in the electrical conductance (i.e., an increase in the electrical resistance) of the subsurface shunt 60 and/or a decrease in the electrical current flowing through the subsurface shunt 60. The shunt mitigator 64 may be configured such that the state change results in a decrease in the electrical conductivity (i.e., an increase in the electrical resistivity) of the subsurface shunt 60 and/or at least a portion of at least one of the electrode assemblies 50 near the subsurface shunt 60.

[0081] The state change may be an electromagnetic state change, an electromagnetic phase transition, a paramagnetic transition, and/or a paraelectric transition. The state change may be a thermodynamic state change, a thermodynamic phase transition, and/or a solid-liquid transition. The state change may be a chemical state change, a chemical decomposition, and/or a polymerization. For example, the shunt mitigator 64 may be

configured to transition, in response to a shunt indicator, to a paramagnetic state, a paraelectric state, a liquid state, a decomposed state, and/or a polymerized state.

[0082] The state change may be associated with a transition temperature of the shunt mitigator 64. The transition temperature may be a temperature between the desired and/or expected temperature of the subsurface region 32 (upon heating) and the temperature associated with an active subsurface shunt 60. For example, the transition temperature may be greater than 200°C, greater than 300°C, greater than 400°C, greater than 500°C, greater than 700°C, less than 1,200°C, less than 1,000°C, less than 900°C, less than 700°C, less than 500°C, less than 400°C, less than 300°C, and/or within a range that includes or is bounded by any of the preceding examples of transition temperatures.

[0083] The transition temperature may be a Curie temperature, a paraelectric transition temperature, a melting point, and/or a solidus temperature. The Curie temperature is the temperature above which a magnetic material becomes paramagnetic (loses its intrinsic magnetization). The paraelectric transition temperature is the temperature above which a dielectric material becomes paraelectric (loses its intrinsic polarization). The magnetic and/or dielectric properties of a material may affect the electrical conductivity of the material when alternating current is applied. Shunt mitigators 64 that undergo a magnetic state transition and/or a dielectric state transition (e.g., the transition temperature is a Curie temperature and/or a paraelectric transition temperature), may have reduced conductivity, may interrupt the electrically conductive path to the subsurface shunt 60, and may reduce the electrical conductance through the subsurface shunt 60. Shunt mitigators 64 configured to undergo a magnetic state transition and/or a dielectric state transition may include, and/or may be, a metal, a metal alloy, and/or a ceramic. For example, the shunt mitigator 64 may include, and/or may be, a bismuth-manganese alloy and/or a strontium titanate compound.

[0084] The shunt mitigator 64 may be, and/or may include, a composite shunt mitigator 66. The composite shunt mitigator 66 may include at least two materials with different functional relationships between properties of the material and the shunt indicator (e.g., a thermal, mechanical, and/or electrical property). The materials of the composite shunt mitigator 66 may include one or more of the materials described with respect to other types of shunt mitigators 64, and may include other materials. The composite shunt mitigator 66 may include a first material with a first functional relationship and a second material with a second functional relationship. The property of the first functional relationship may be an electrical property such as electrical conductivity, electrical admittivity, electrical resistivity, electrical

impeditivity, electric susceptibility, electric permittivity, magnetic susceptibility, and/or magnetic permeability. The property of the second functional relationship may be an electrical property, a physical property, and/or a chemical property. For example, the property of the second functional relationship may be electrical conductivity, electrical admittivity, electrical resistivity, electrical impeditivity, electric susceptibility, electric permittivity, magnetic susceptibility, magnetic permeability, density, viscosity, volume, rigidity, and/or chemical activity. The combination of the functional relationships of the materials in a composite shunt mitigator 66 may be configured to produce a composite functional relationship between one or more properties of the composite shunt mitigator 66 and the shunt indicator. The composite functional relationship may be a non-monotonic functional relationship, e.g., defining a mathematical extremum (maximum, minimum, inflection point, etc.) within the expected operating range of bulk heating system 10 and/or near the shunt indicator (e.g., at a predetermined value of a thermal, mechanical, and/or electrical property of the bulk heating system 10, the subsurface region 32, one or more of the electrode assemblies 50, and/or the subsurface shunt 60).

[0085] The shunt mitigator 64 may be configured to maintain a property of the shunt mitigator 64 in the presence of a subsurface shunt 60. The shunt mitigator 64 may be configured such that the placement and/or location of the shunt mitigator 64 within and/or near the subsurface shunt 60 results in a decrease in the electrical conductance (i.e., an increase in the electrical resistance) of the subsurface shunt 60 and/or a decrease in the electrical current flowing through the subsurface shunt 60. The placement and/or location of the shunt mitigator 64 may result in a decrease in the electrical conductivity (i.e., an increase in the electrical resistivity) of the subsurface shunt 60 and/or at least a portion of at least one of the electrode assemblies 50 near the subsurface shunt 60. The property of the shunt mitigator 64 may include at least one of electrical conductivity, electrical admittivity, electrical resistivity, electrical impeditivity, electric susceptibility, electric permittivity, magnetic susceptibility, magnetic permeability, density, viscosity, volume, and chemical activity.

[0086] For example, the shunt mitigator 64 may include, and/or may be, an electrically insulating liquid, such as mineral oil, transformer oil, and/or a polymer. The electrically insulating liquid may be configured to maintain its electrically insulating property in the presence of a subsurface shunt 60, e.g., at the temperature and/or electrical current that may be associated with the subsurface shunt 60. The electrically insulating liquid may not be

present in the electrode assemblies 50 and/or the subsurface region 32 before the formation of a subsurface shunt 60. Once the subsurface shunt 60 is formed and the presence of the subsurface shunt 60 is detected, the electrically insulating liquid may be injected into at least one of the electrode assemblies 50 and flowed to and/or into the subsurface shunt 60, thereby applying an electrically insulating mask to the subsurface shunt 60 and decreasing the electrical conductance through the subsurface shunt 60.

[0087] Subsurface shunts 60 may be mitigated during bulk heating of subsurface formations 20 by performing bulk heating methods 100. In the example of Fig. 2, bulk heating methods 100 may include electrically powering 110 at least a pair of electrode assemblies (such as electrode assemblies 50) that are within a subsurface formation (such as subsurface formation 20), to resistively heat at least a subsurface region (such as subsurface region 32 and/or *in situ* resistive heater 34) between the pair of electrode assemblies with electrical current flowing through the subsurface region between the pair of electrode assemblies. The bulk heating methods 100 may include flowing 112 shunt mitigator (such as shunt mitigator 64) into at least one of the electrode assemblies. Responsive to a shunt indicator that indicates the presence and/or formation of a subsurface shunt (such as subsurface shunt 60) between the pair of electrode assemblies, the bulk heating methods 100 may include mitigating 114 the subsurface shunt with the shunt mitigator.

[0088] Electrically powering 110 may include applying a voltage across and/or supplying an electrical current through the pair of electrode assemblies. Electrically powering 110 may include supplying an AC current (i.e., an alternating current) to the pair of electrode assemblies. Electrically powering 110 may include electrically powering the pair of electrode assemblies while at least one of the electrode assemblies includes the shunt mitigator. For example, electrically powering 110 may include electrically powering the electrode assembly configuration of Fig. 1, where shunt mitigator 64 may be present in one or both of the electrode assemblies 50 and/or in the subsurface region 32 between the electrode assemblies 50.

[0089] Electrically powering 110 may include heating the subsurface region to pyrolyze organic matter in the subsurface formation, to pyrolyze organic matter to create hydrocarbon fluids, and/or to mobilize hydrocarbon fluids within the subsurface formation. Electrically powering 110 may include heating the subsurface region to an average temperature and/or a point (localized) temperature of at least 150°C, at least 250°C, at least 350°C, at least 450°C, at least 550°C, at least 700°C, at least 800°C, at least 900°C, at most 1000°C, at most 900°C,

at most 800°C, at most 700°C, at most 550°C, at most 450°C, at most 350°C, at most 270°C, and/or within a range that includes or is bounded by any of the preceding examples of temperature.

[0090] Electrically powering 110 to resistively heat the subsurface region may include forming an electrical circuit between the electrode assemblies and the subsurface region. Electrically powering 110 may include electrically powering the subsurface region to form an *in situ* resistive heater (such as *in situ* resistive heater 34) between the electrode assemblies.

[0091] Electrically powering 110 may begin without a subsurface shunt being present between the electrode assemblies. Electrically powering 110 may result in a subsurface shunt forming between the electrode assemblies within the subsurface region (and/or within the *in situ* resistive heater).

[0092] Bulk heating methods 100 of Fig. 2 may include flowing 112 the shunt mitigator into at least one of the electrode assemblies. Flowing 112 may be performed before, during, and/or after electrically powering 110 and/or before, during, and/or after the formation of the subsurface shunt.

[0093] Flowing 112 may include injecting a slurry and/or a fluid that includes, and/or is, the shunt mitigator into at least one of the electrode assemblies. Flowing 112 may include flowing shunt mitigator into the subsurface region, the *in situ* resistive heater, and/or the subsurface shunt. Flowing 112 may include applying a pressure differential between the pair of electrode assemblies (e.g., injecting into one electrode assembly while drawing a hydrostatic pressure on the other electrode assembly). As shown in Fig. 1, flowing 112 may result in a bulk heating system 10 with shunt mitigator 64 within the electrode assemblies 50, the subsurface region 32, the *in situ* resistive heater 34, and/or the subsurface shunt 60 (if present). Flowing 112 may result in shunt mitigator 64 selectively located near and/or within the subsurface shunt 60.

[0094] Flowing 112 may be performed before, during, and/or after determining 116 the presence of the subsurface shunt between the electrode assemblies. Determining 116 may include measuring an electrical conductivity-related parameter between the pair of electrode assemblies. The electrical conductivity-related parameter may include, and/or may be, conductivity, conductance, resistivity, resistance, admittivity, admittance, impeditivity, impedance, current, voltage, a point temperature and/or an average temperature. Determining

116 may include measuring a fluid permeability-related parameter between the pair of electrode assemblies.

[0095] For example, determining 116 may include determining that the average electrical conductivity of the subsurface shunt is at least 10^{-5} S/m, at least 10^{-4} S/m, at least 10^{-3} S/m, at least 0.01 S/m, at least 0.1 S/m, at least 1 S/m, at least 10 S/m, at least 100 S/m, at least 300 S/m, at least 1,000 S/m, at least 3,000 S/m, at least 10,000 S/m, and/or within a range that includes or is bounded by any of the preceding examples of average electrical conductivity. Determining 116 may include determining that the average electrical conductivity of the subsurface region is at least 10^{-5} S/m, at least 10^{-4} S/m, at least 10^{-3} S/m, at least 0.01 S/m, at least 0.1 S/m, at least 1 S/m, at least 10 S/m, at least 100 S/m, and/or within a range that includes or is bounded by any of the preceding examples of average electrical conductivity.

[0096] Bulk heating methods 100 of Fig. 2 may include mitigating 114, responsive to the shunt indicator, the subsurface shunt between the pair of electrode assemblies with the shunt mitigator. Prior to mitigating 114, and as shown in Fig. 3, the subsurface shunt 60 has formed (or has begun to form) and shunt mitigator 64 may be present near and/or within the subsurface shunt 60. As discussed, the shunt mitigator 64 may be located near and/or within the subsurface shunt 60 by flowing 112 the shunt mitigator into at least one of the electrode assemblies 50. The shunt mitigator 64 may be present prior to the formation of the subsurface shunt 60 and/or may be located near and/or within the subsurface shunt 60 after the formation of the subsurface shunt 60.

[0097] Once the shunt mitigator 64 is present near and/or within the subsurface shunt 60 and the subsurface shunt 60 exhibits a shunt indicator (e.g., a thermal, mechanical, and/or electrical parameter value and/or change in value), the shunt mitigator 64 may selectively attenuate and/or eliminate electrical current (and/or the possibility of electrical current transmission) through the subsurface shunt 60. The shunt mitigator 64 may selectively attenuate and/or eliminate electrical current (and/or the possibility of electrical current transmission) through the subsurface shunt 60 by being selectively located near and/or within the subsurface shunt 60 and/or by changing a property in response to the shunt indicator.

[0098] Returning to Fig. 2, mitigating 114 may be performed before, during, and/or after determining 116 the presence of the subsurface shunt between the electrode assemblies. Upon determining 116 the presence of the subsurface shunt, mitigating 114 may prompt flowing 112 the shunt mitigator to mitigate the subsurface shunt.

[0099] Mitigating 114 may include decreasing the electrical conductance (i.e., increasing the electrical resistance) of the subsurface shunt. Mitigating 114 may include electrically isolating the subsurface shunt from one or more of the electrode assemblies.

[00100] Mitigating 114 may include forming a modified subsurface region, as illustrated in Fig. 4. Mitigating 114 may include forming a mitigated subsurface shunt 62 from the subsurface shunt 60 and thereby forming a modified *in situ* resistive heater 36, which includes the mitigated subsurface shunt 62, from the *in situ* resistive heater 34.

[00101] After mitigating 114, the electrode assemblies may have reduced electrical conductivity. Bulk heating methods 100 may include, after the mitigating 114, introducing electrically conductive material into at least one of the electrode assemblies. Electrically conductive material may include granular material, granules, particles, filaments, metal, granular metal, metal coated particles, coke, graphite, electrically conductive gel, and/or electrically conductive liquid.

[00102] Bulk heating methods 100 may include electrically powering the pair of electrode assemblies 50 to resistively heat the modified *in situ* resistive heater 36 with electrical current flowing through the modified *in situ* resistive heater between the pair of electrode assemblies 50.

[00103] Bulk heating methods 100 may include monitoring the bulk heating system 10 for shunt indicators. For example, bulk heating methods 100 may include measuring one or more electrical conductivity-related parameters and/or fluid permeability-related parameters between the pair of electrode assemblies.

[00104] Fig. 5 schematically represents an example of bulk heating methods 100 which may or may not utilize a shunt mitigator. Bulk heating methods 100 of Fig. 5 may include electrically powering 110 the pair of electrode assemblies to resistively heat an *in situ* resistive heater between the pair of electrodes. The bulk heating methods 100 may include determining 116 the presence of the subsurface shunt between the pair of electrode assemblies. Determining 116 may be similar and/or identical to the determining described above with respect to Figure 2. Upon determining 116, the bulk heating methods 100 may include mitigating 114 the subsurface shunt to form a modified *in situ* resistive heater. The bulk heating methods 100 may include electrically powering 118 the pair of electrode assemblies to resistively heat the modified *in situ* resistive heater. Electrically powering 118

may be similar and/or identical to the electrically powering described above with respect to Figure 2.

[00105] Though mitigating 114 of the example of Fig. 5 may include aspects or features described with respect to the example of Fig. 2, mitigating 114 may include methods of mitigation that do not utilize a shunt mitigator. Mitigating 114 may include thermal-electrical ablation of at least a portion of the subsurface shunt. Thermal-electric ablation may include applying a relatively large impulse of electrical power to the subsurface shunt, by applying such impulse to the pair of electrode assemblies. The impulse of electrical power may be configured to selectively heat the subsurface shunt and/or at least a portion of the electrode assemblies near the subsurface shunt due to the electrical conductivity of the subsurface shunt. The heating due to the impulse of electrical power may thermally-electrically ablate at least a portion of the subsurface shunt, or at least a portion of one of the electrode assemblies near the subsurface shunt, much like blowing a fuse. After the thermal-electric ablation, the subsurface shunt may be electrically isolated from at least one of the electrode assemblies and/or may include an electrical discontinuity. The impulse of electrical power may be at least 1,000 V, at least 10,000 V, and/or at least 100,000 V. The impulse of electrical power may be applied for less than 10 seconds, less than 1 second, less than 0.1 seconds, and/or less than 0.01 seconds. In the example of Fig. 2, mitigating 114 may include thermally-electrically ablating as described.

[00106] Bulk heating methods 100 may include producing hydrocarbon fluids from the subsurface formation. The hydrocarbon fluids may be produced to the surface via a production well in the subsurface formation. The production well may be proximate to one or more of the electrode assemblies. The production well may be in fluid communication with one or more subsurface regions.

[00107] The various disclosed elements of systems and steps of methods disclosed herein are not required of all systems and methods according to the present disclosure, and the present disclosure includes all novel and non-obvious combinations and subcombinations of the various elements and steps disclosed herein. Moreover, one or more of the various elements and steps disclosed herein may define independent inventive subject matter that is separate and apart from the whole of a disclosed apparatus or method. Accordingly, such inventive subject matter is not required to be associated with the specific systems and methods that are expressly disclosed herein, and such inventive subject matter may find utility in systems and/or methods that are not expressly disclosed herein.

[00108] In the present disclosure, several examples have been discussed and/or presented in the context of flow diagrams, or flow charts, in which the methods are shown and described as a series of blocks, or steps. Unless specifically set forth in the accompanying description, the order of the blocks may vary from the illustrated order in the flow diagram, including with two or more of the blocks (or steps) occurring in a different order and/or concurrently.

Industrial Applicability

[00109] The systems and methods of the present disclosure are applicable to the oil and gas industry.

[00110] It is believed that the following claims particularly point out certain combinations and subcombinations that are novel and non-obvious. Other combinations and subcombinations of features, functions, elements and/or properties may be claimed through amendment of the present claims or presentation of new claims in this or a related application. Such amended or new claims, whether different, broader, narrower, or equal in scope to the original claims, are also regarded as included within the subject matter of the present disclosure.

CLAIMS

1. A method for bulk heating a subsurface formation with at least a pair of electrode assemblies in the subsurface formation, the method comprising:

electrically powering the pair of electrode assemblies to resistively heat a subsurface region between the pair of electrode assemblies with electrical current flowing through the subsurface region between the pair of electrode assemblies;

flowing a shunt mitigator into at least one of the pair of electrode assemblies; and

responsive to a shunt indicator, mitigating a subsurface shunt between the pair of electrode assemblies with the shunt mitigator, wherein the shunt indicator indicates a presence of the subsurface shunt.

2. The method of claim 1, wherein the flowing occurs after determining the presence of the subsurface shunt.

3. The method of claim 2, wherein the determining comprises measuring between the pair of electrode assemblies at least one of an electrical conductivity-related parameter, a thermal parameter, and a fluid permeability-related parameter.

4. The method of any of claims 2-3, wherein the determining comprises determining that an average electrical conductivity of the subsurface region is at least 0.01 S/m.

5. The method of any of claims 1-4, wherein the flowing occurs one of before, during and after the electrically powering.

6. The method of any of claims 1-5, wherein the shunt indicator is at least one of a temperature difference in the subsurface region, a temperature gradient in the subsurface region, a current density in the subsurface region, a current gradient in the subsurface region, a current density in the subsurface shunt, an electrical conductivity of the subsurface shunt, an electrical admittivity of the subsurface shunt, an electrical resistivity of the subsurface shunt, an electrical impeditivity of the subsurface shunt, a point temperature of at least one electrode assembly, a point temperature near the subsurface shunt, and an average temperature of the subsurface shunt.

7. The method of any of claims 1-6, wherein the shunt mitigator is selected to change a property in response to the shunt indicator.

8. The method of claim 7, wherein the mitigating comprises mitigating the subsurface shunt with the change of the property of the shunt mitigator.

9. The method of any of claims 7-8, wherein the shunt mitigator is configured to decrease the electrical current flowing through the subsurface shunt by changing the property in response to the shunt indicator.

10. The method of any of claims 7-9, wherein the property is at least one of electrical conductivity, electrical admittivity, electrical resistivity, electrical impeditivity, electric susceptibility, electric permittivity, magnetic susceptibility, magnetic permeability, density, viscosity, volume, and chemical activity.

11. The method of any of claims 1-10, wherein the shunt mitigator is configured to one of decrease and increase the electrical conductance of the subsurface shunt.

12. The method of any of claims 1-11, wherein the shunt mitigator is configured to decrease the electrical conductivity of at least a portion of the one of the pair of electrode assemblies near the subsurface shunt.

13. The method of any of claims 1-12, wherein the shunt mitigator is configured to increase the electrical resistivity of at least a portion of the one of the pair of electrode assemblies near the subsurface shunt.

14. The method of any of claims 1-13, wherein the shunt mitigator is selected to at least one of decompose in response to the shunt indicator, polymerize in response to the shunt indicator, and melt in response to the shunt indicator.

15. The method of any of claims 1-14, wherein the shunt mitigator is selected to chemically react, in response to the shunt indicator, with at least one of the one of the pair of electrode assemblies, the subsurface region, and the subsurface shunt.

16. The method of any of claims 1-15, wherein the shunt mitigator is selected to undergo a state change in response to the shunt indicator.

17. The method of claim 16, wherein the shunt indicator undergoes a state change, and the state change is at least one of an electromagnetic state change, an electromagnetic phase transition, a paramagnetic transition, and a paraelectric transition.

18. The method of any of claims 16-17, wherein the state change is at least one of a thermodynamic state change, a thermodynamic phase transition, and a solid-liquid transition.

19. The method of any of claims 16-18, wherein the state change is at least one of a chemical state change, a chemical decomposition, and a polymerization.

20. The method of any of claims 16-19, wherein the shunt mitigator is selected to transition, in response to the shunt indicator, to at least one of a paramagnetic state and a paraelectric state.

21. The method of any of claims 16-20, wherein the shunt mitigator is selected to transition, in response to the shunt indicator, to a liquid state.

22. The method of any of claims 16-21, wherein the shunt mitigator is selected to transition, in response to the shunt indicator, to at least one of a decomposed state and a polymerized state.

23. The method of any of claims 16-22, wherein the state change is associated with a transition temperature of the shunt mitigator.

24. The method of claim 23, wherein the transition temperature is greater than 500°C.

25. The method of any of claims 23-24, wherein the transition temperature is at least one of a Curie temperature, a paraelectric transition temperature, a melting point, and a solidus temperature.

26. The method of any of claims 1-25, wherein the shunt mitigator includes a composite shunt mitigator, wherein the composite shunt mitigator includes a first material that defines a first functional relationship between an electrical property of the first material and the shunt indicator, and wherein the composite shunt mitigator includes a second material that defines a second functional relationship between a property of the second material and the shunt indicator.

27. The method of claim 26, wherein the electrical property of the first material includes at least one of electrical conductivity, electrical admittivity, electrical resistivity, electrical impeditivity, electric susceptibility, electric permittivity, magnetic susceptibility, and magnetic permeability.

28. The method of any of claims 26-27, wherein the property of the second material includes at least one of electrical conductivity, electrical admittivity, electrical resistivity, electrical impeditivity, electric susceptibility, electric permittivity, magnetic susceptibility, magnetic permeability, density, viscosity, volume, rigidity, and chemical activity.

29. The method of any of claims 1-28, wherein at least one of the pair of electrode assemblies includes a fracture.

30. The method of claim 29, wherein the fracture comprises proppant that includes at least one of electrically conductive material and electrically conductive granular material.

31. The method of any of claims 29-30, wherein the fracture is one of substantially vertical and substantially horizontal.

32. The method of any of claims 29-31, wherein the pair of electrode assemblies includes a first electrode assembly and a second electrode assembly, wherein the first electrode assembly includes a first fracture, the second electrode assembly includes a second fracture, and wherein the first fracture and the second fracture are substantially parallel.

33. The method of any of claims 1-32, wherein each electrode assembly of the pair of electrode assemblies includes an electrically conductive material that includes at least one of granular material, granules, particles, filaments, metal, granular metal, metal coated particles, coke, graphite, electrically conductive gel, and electrically conductive liquid.

34. The method of any of claims 1-33, wherein the electrically powering includes electrically powering the pair of electrode assemblies while at least the one of the pair of electrode assemblies includes the shunt mitigator.

35. The method of any of claims 1-34, wherein the mitigating includes forming a mitigated subsurface shunt from the subsurface shunt and thereby forming a modified subsurface region with the mitigated subsurface shunt from the subsurface region, and wherein the method further comprises electrically powering the pair of electrode assemblies to resistively heat the modified subsurface region with electrical current flowing through the modified subsurface region between the pair of electrode assemblies.

36. The method of any of claims 1-35, wherein the electrically powering includes heating the subsurface region to an average temperature of at least 250°C.

37. The method of any of claims 1-36, wherein the electrically powering includes heating organic matter in the subsurface formation to generate mobile hydrocarbon fluids.

38. The method of any of claims 1-37, further comprising producing hydrocarbon fluids from the subsurface formation.

39. A method for bulk heating a subsurface formation with at least a pair of electrode assemblies in the subsurface formation, the method comprising:

electrically powering the pair of electrode assemblies to resistively heat an *in situ* resistive heater, wherein the *in situ* resistive heater is a subsurface region of the subsurface formation between the pair of electrode assemblies;

upon determining a presence of a subsurface shunt between the pair of electrode assemblies, forming a modified *in situ* resistive heater by mitigating the subsurface shunt; and

electrically powering the pair of electrode assemblies to resistively heat the modified *in situ* resistive heater.

40. The method of claim 39, wherein the mitigating includes decreasing the electrical conductance of the subsurface shunt.

41. The method of any of claims 39-40, wherein the mitigating includes increasing the electrical resistance of the subsurface shunt.

42. The method of any of claims 39-41, wherein the mitigating includes electrically isolating the subsurface shunt from at least one of the pair of electrode assemblies.

43. The method of any of claims 39-42, wherein the mitigating includes mitigating the subsurface shunt with a shunt mitigator.

44. The method of claim 43, wherein the mitigating includes flowing the shunt mitigator into at least one of the pair of electrode assemblies.

45. The method of any of claims 43-44, wherein the shunt mitigator is configured to decrease the electrical conductance of the subsurface shunt.

46. The method of any of claims 43-45, wherein the shunt mitigator is configured to increase the electrical resistance of the subsurface shunt.

47. The method of any of claims 43-46, wherein the shunt mitigator is configured to decrease the electrical conductivity of at least a portion of an electrode assembly of the pair of electrode assemblies near the subsurface shunt.

48. The method of any of claims 43-47, wherein the shunt mitigator is configured to increase the electrical resistivity of at least a portion of an electrode assembly of the pair of electrode assemblies near the subsurface shunt.

49. The method of any of claims 43-48, wherein the shunt mitigator is selected to chemically react with at least one of an electrode assembly of the pair of electrode assemblies and the subsurface shunt.

50. The method of any of claims 39-49, wherein the mitigating includes injecting a fluid to chemically alter an electrical property of the subsurface shunt.

51. The method of claim 50, wherein the fluid includes at least one of molecular oxygen, carbon dioxide, an oxidizing gas, and a gasification gas.

52. The method of any of claims 39-51, wherein the mitigating includes injecting an electrically insulating liquid into the subsurface shunt.

53. The method of any of claims 39-52, wherein the mitigating includes thermally-electrically ablating at least a portion of the subsurface shunt.

54. The method of any of claims 39-53, further comprising, after the mitigating, introducing electrically conductive material into at least one of the pair of electrode assemblies.

55. A subsurface formation, comprising:

at least a pair of electrode assemblies;

wherein each electrode assembly of the pair of electrode assemblies includes an electrically conductive material; and

wherein at least one electrode assembly of the pair of electrode assemblies includes a shunt mitigator that is selected to undergo a state change in response to a shunt indicator.

56. The subsurface formation of claim 55, wherein the shunt indicator indicates a presence of a subsurface shunt between the pair of electrode assemblies.

57. The subsurface formation of any of claims 55-56, wherein the shunt indicator is at least one of a temperature difference in the subsurface region, a temperature gradient in the subsurface region, a current density in the subsurface region, a current gradient in the subsurface region, a current density in the subsurface shunt, an electrical conductivity of the subsurface shunt, an electrical admittivity of the subsurface shunt, an electrical resistivity of the subsurface shunt, an electrical impeditivity of the subsurface shunt, a point temperature of

at least one electrode assembly, a point temperature near the subsurface shunt, and an average temperature of the subsurface shunt.

58. The subsurface formation of any of claims 55-57, wherein the shunt mitigator undergoes a state change, and the state change is at least one of an electromagnetic state change, an electromagnetic phase transition, a paramagnetic transition, and a paraelectric transition.

59. The subsurface formation of any of claims 55-58, wherein the state change is at least one of a thermodynamic state change, a thermodynamic phase transition, and a solid-liquid transition.

60. The subsurface formation of any of claims 55-59, wherein the state change is at least one of a chemical state change, a chemical decomposition, and a polymerization.

61. The subsurface formation of any of claims 55-60, wherein the shunt mitigator is selected to transition, in response to the shunt indicator, to at least one of a paramagnetic state and a paraelectric state.

62. The subsurface formation of any of claims 55-61, wherein the shunt mitigator is selected to transition, in response to the shunt indicator, to a liquid state.

63. The subsurface formation of any of claims 55-62, wherein the shunt mitigator is selected to transition, in response to the shunt indicator, to at least one of a decomposed state and a polymerized state.

64. The subsurface formation of any of claims 55-63, wherein the state change is associated with a transition temperature of the shunt mitigator.

65. The subsurface formation of claim 64, wherein the transition temperature is greater than 500°C.

66. The subsurface formation of any of claims 64-65, wherein the transition temperature is at least one of a Curie temperature, a paraelectric transition temperature, a melting point, and a solidus temperature.

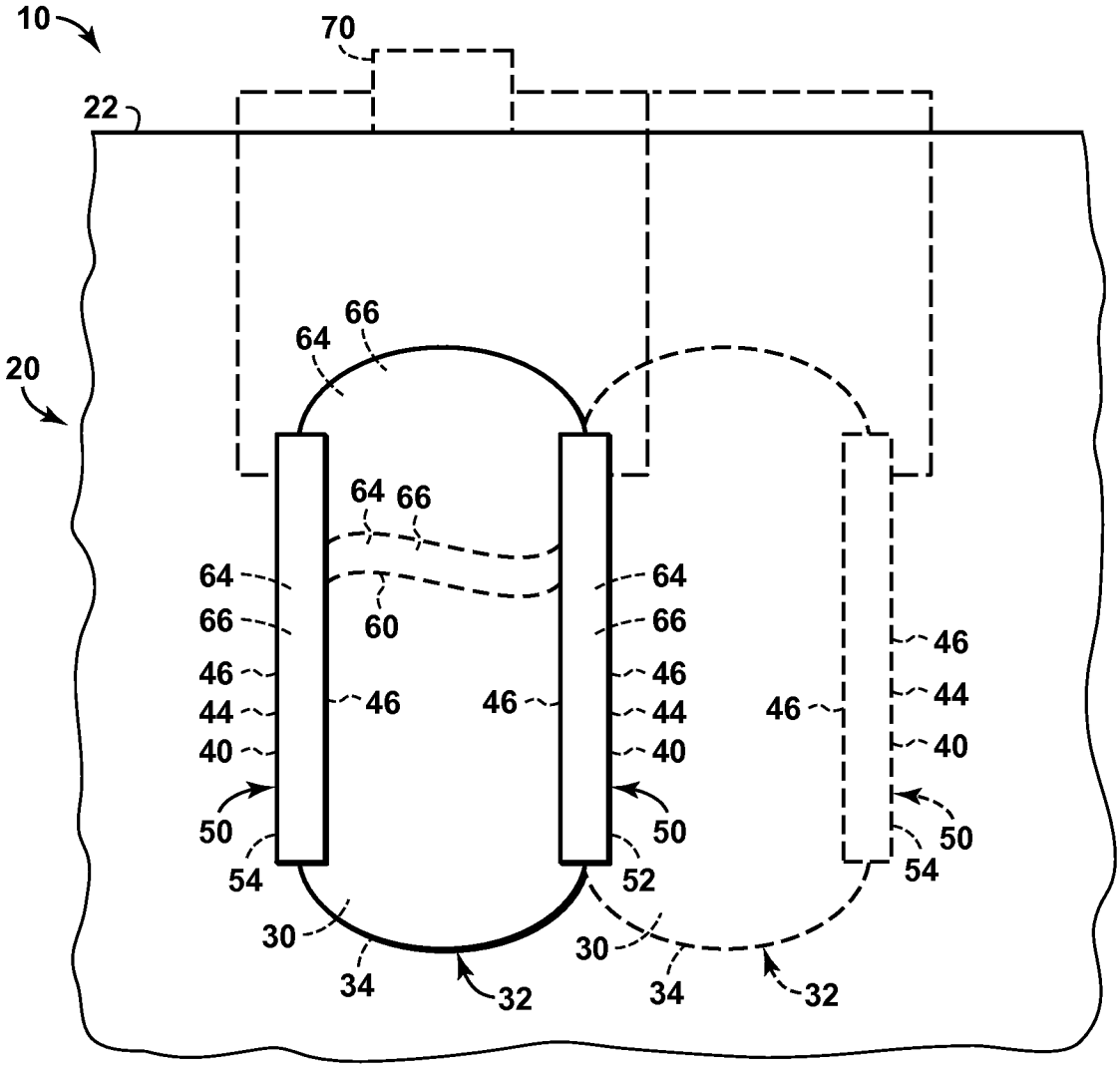

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FIG. 1

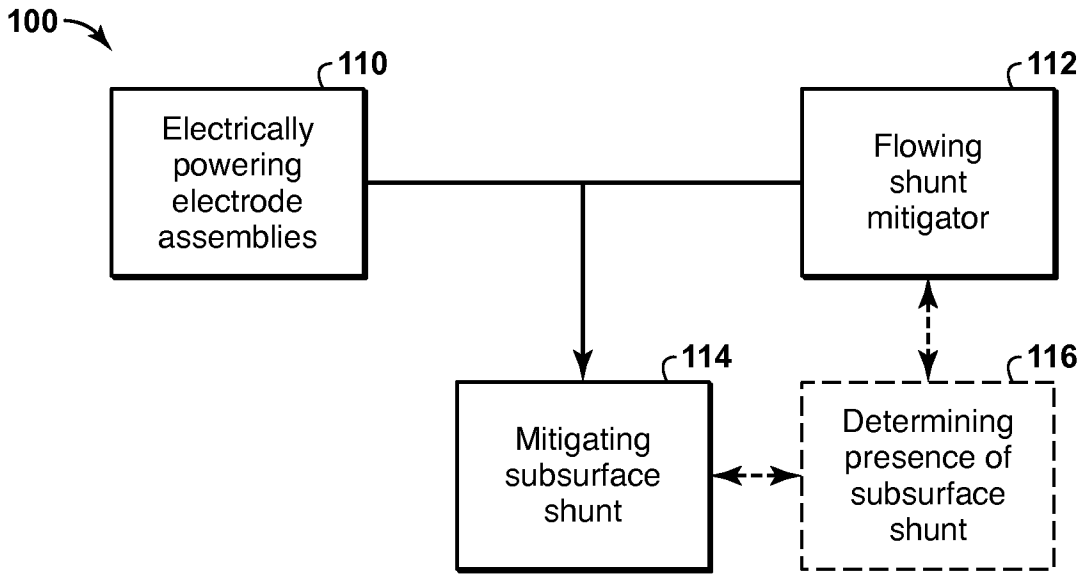

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Electrically powering electrode assemblies
112
Flowing shunt mitigator
114
Mitigating subsurface shunt
116
Determining presence of subsurface shunt

FIG. 2

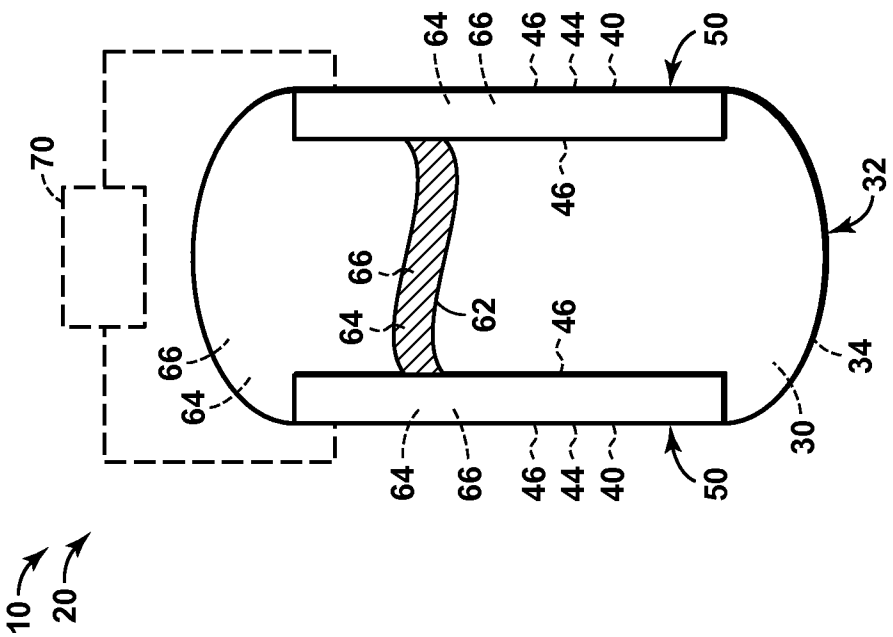

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FIG. 4

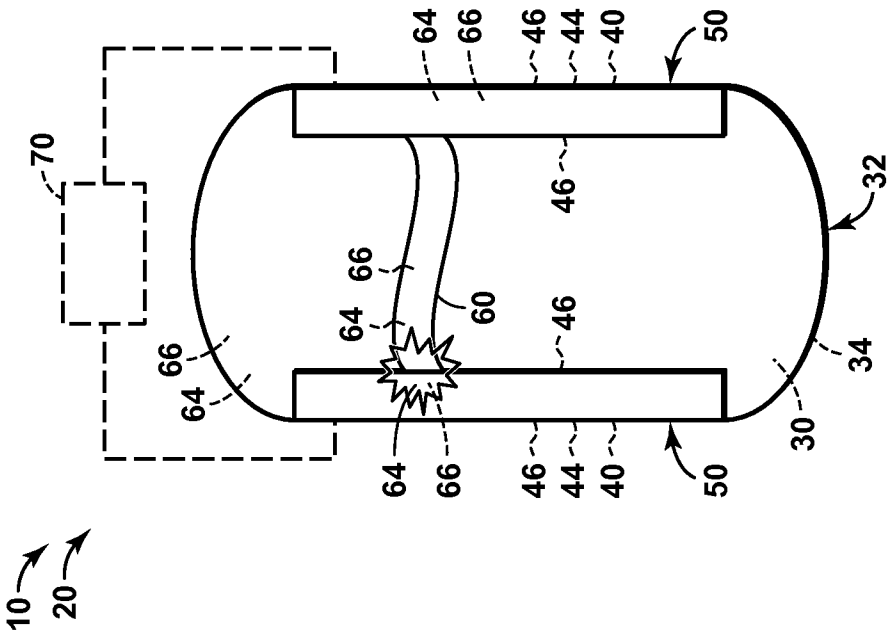

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FIG. 3

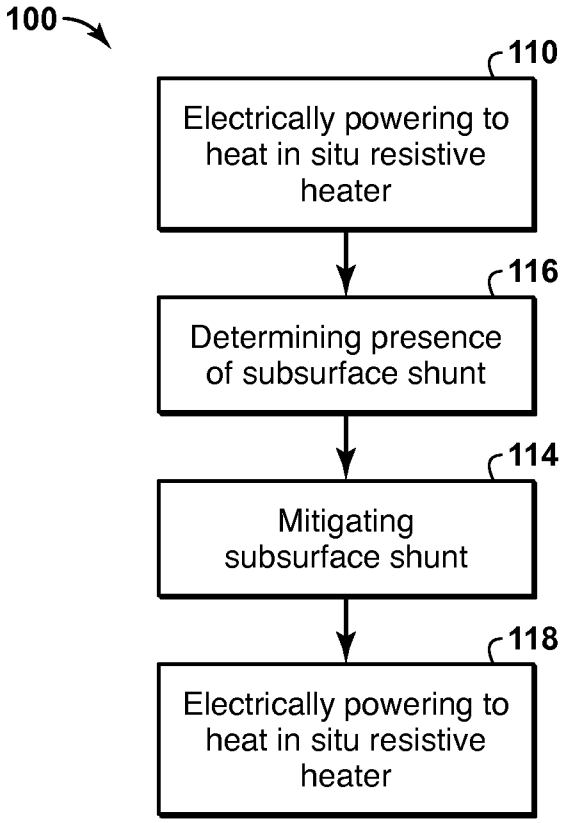

100
110
Electrically powering to heat in situ resistive heater
116
Determining presence of subsurface shunt
114
Mitigating subsurface shunt
118
Electrically powering to heat in situ resistive heater

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2015/056807

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

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
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.
X	WO 2010/129174 A1 (EXXONMOBIL UPSTREAM RES CO [US]; STONE MATTHEW [US]; GHURYE GANESH [US) 11 November 2010 (2010-11-11) paragraphs [0101], [0179], [0224] - [0227]; figure 7	1-15, 26-32, 34-53
A	US 2010/101793 A1 (SYMINGTON WILLIAM A [US] ET AL) 29 April 2010 (2010-04-29) paragraphs [0020] - [0022], [0144], [0191], [0258], [0259]	1-15, 26-32, 34-53
A	US 2014/096951 A1 (HOCKING GRANT [US]) 10 April 2014 (2014-04-10) paragraphs [0011], [0057], [0058], [0061]	1-15, 26-32, 34-53

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 January 2016	11/04/2016

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Schneiderbauer, K

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/056807

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-15, 26-32, 34-53

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2015/056807

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2010129174 A1	11-11-2010	AU 2010245127 A1	24-11-2011
		CA 2757483 A1	11-11-2010
		CN 102421988 A	18-04-2012
		IL 214873 A	30-06-2014
		JO 2836 B	15-09-2014
		US 2010282460 A1	11-11-2010
		WO 2010129174 A1	11-11-2010
US 2010101793 A1	29-04-2010	AU 2009310318 A1	06-05-2010
		BR PI0919650 A2	08-12-2015
		CA 2738873 A1	06-05-2010
		CN 102203379 A	28-09-2011
		US 2010101793 A1	29-04-2010
		WO 2010051093 A1	06-05-2010
US 2014096951 A1	10-04-2014	CA 2829033 A1	04-04-2014
		US 2014096951 A1	10-04-2014

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-15, 26-32, 34-53

   Bulk heating with a pair of electrode assemblies and a shunt mitigator responsive to a shunt indicator.

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2. claims: 33, 54-57

   Each electrode assembly of a pair of electrode assemblies of a bulk heater includes an electrically conductive material.

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3. claims: 16-25, 58-66

   Shunt mitigator which undergoes a change of state in response to the shunt indicator.
