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(54) ELECTRICALLY CONDUCTIVE METHODS FOR HEATING A SUBSURFACE FORMATION TO CONVERT ORGANIC MATTER INTO HYDROCARBON FLUIDS

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Publication Classification

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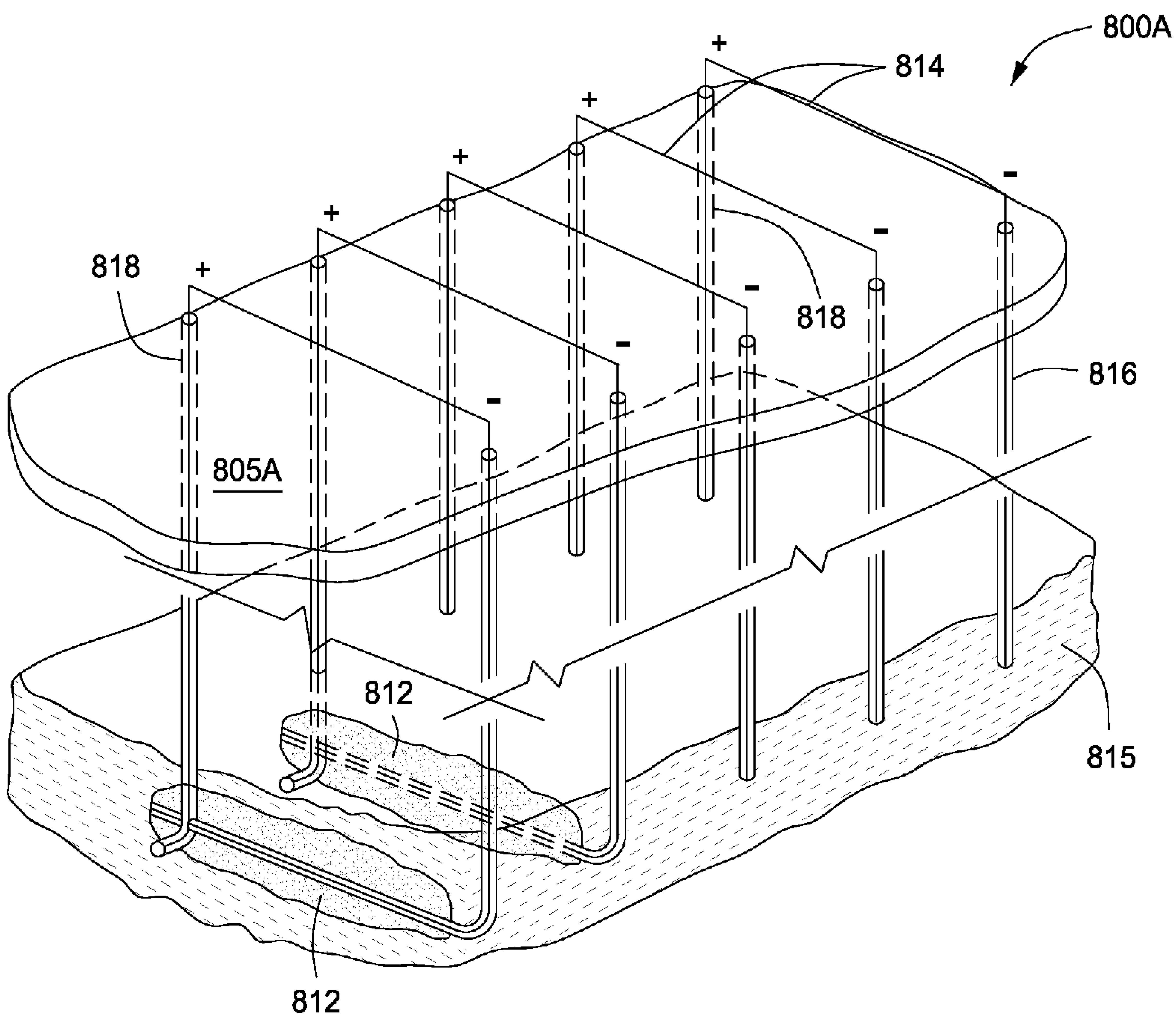
E21B 36/00 (2006.01)

(52) **U.S. Cl.** **166/302**; 166/60

(57) **ABSTRACT**

A method and system for heating a subsurface formation using electrical resistance heating is provided. In one aspect, two or more wellbores are provided that penetrate an interval of solid organic-rich rock within the subsurface formation. At least one fracture is established in the organic-rich rock from at least one of the wellbores, and electrically conductive material is provided in the fracture. In this way electrical communication is provided between the two or more wellbores. The electrically conductive material may include a first portion placed in contact with each of the two or more wellbores, and a second portion intermediate the two or more wellbores. The first portion has a first bulk resistivity while the second portion has a second bulk resistivity. The method also includes passing electric current through the fracture such that heat is generated by electrical resistivity within the electrically conductive material sufficient to pyrolyze at least a portion of the organic-rich rock into hydrocarbon fluids. The resistive heat generated within the first portion of the electrically conductive material is less than the heat generated within the second portion of the electrically conductive material.



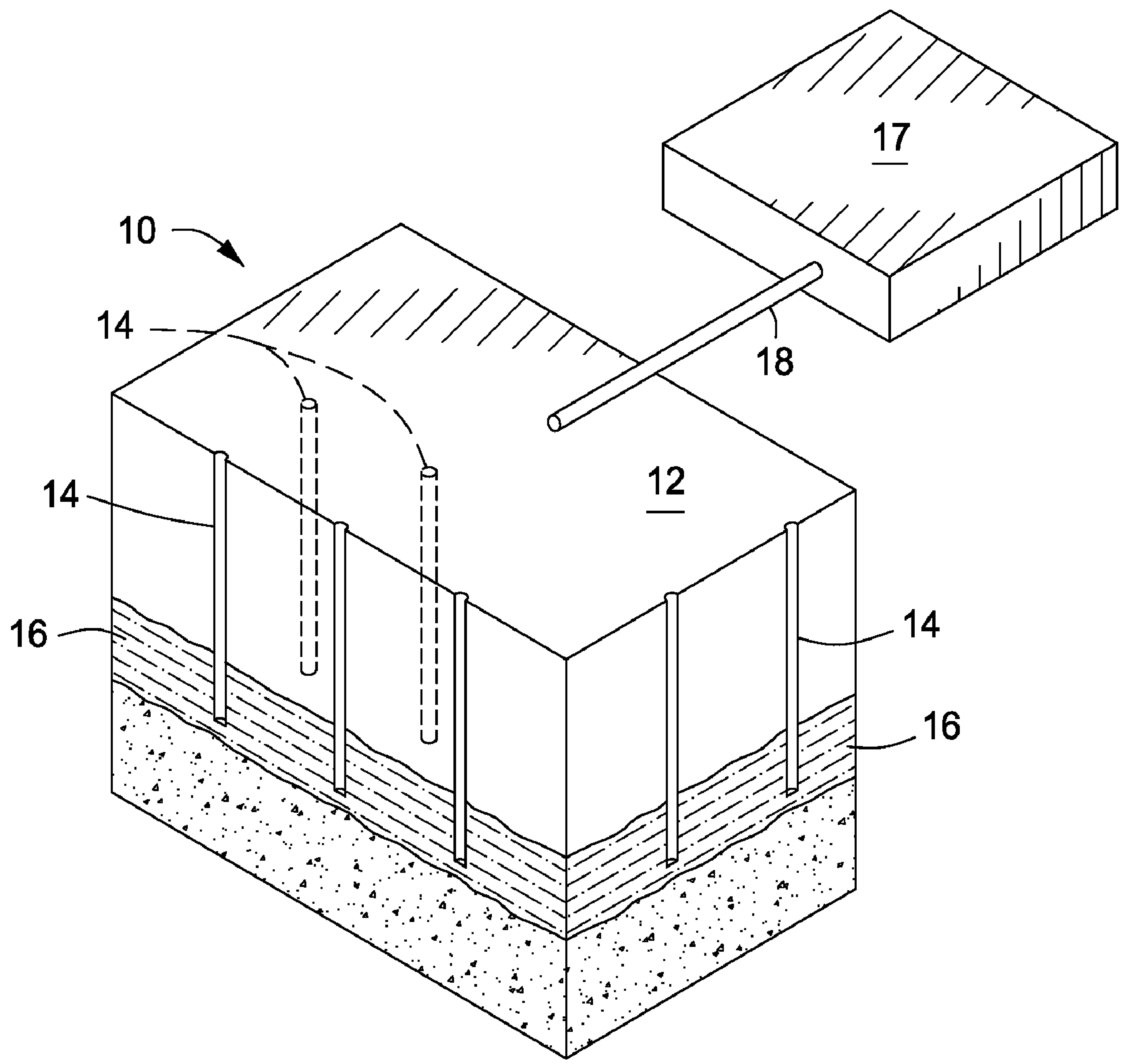


FIG. 1

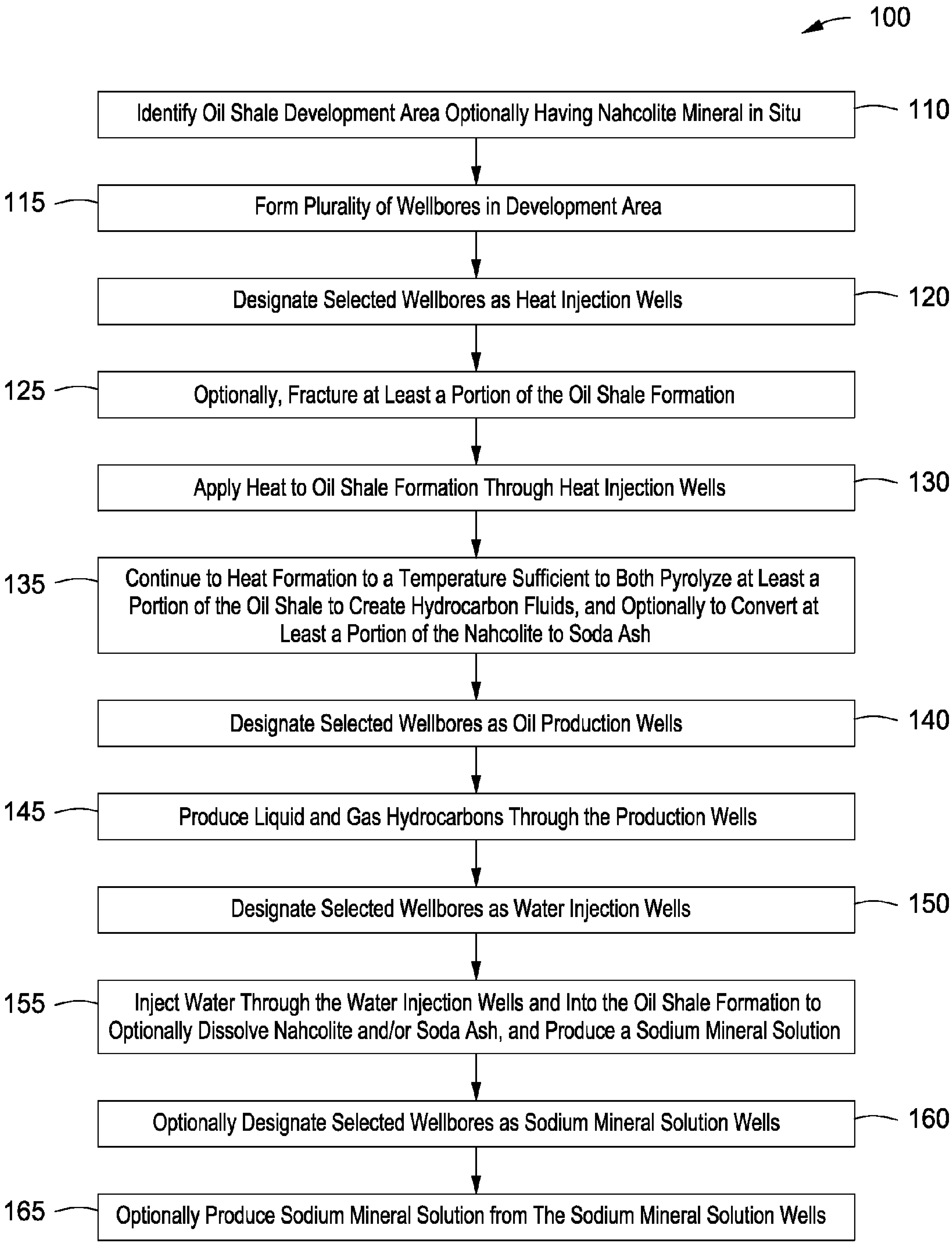

100
Identify Oil Shale Development Area Optionally Having Nahcolite Mineral in Situ
110
115
Form Plurality of Wellbores in Development Area
Designate Selected Wellbores as Heat Injection Wells
120
125
Optionally, Fracture at Least a Portion of the Oil Shale Formation
Apply Heat to Oil Shale Formation Through Heat Injection Wells
130
135
Continue to Heat Formation to a Temperature Sufficient to Both Pyrolyze at Least a Portion of the Oil Shale to Create Hydrocarbon Fluids, and Optionally to Convert at Least a Portion of the Nahcolite to Soda Ash
Designate Selected Wellbores as Oil Production Wells
140
145
Produce Liquid and Gas Hydrocarbons Through the Production Wells
Designate Selected Wellbores as Water Injection Wells
150
155
Inject Water Through the Water Injection Wells and Into the Oil Shale Formation to Optionally Dissolve Nahcolite and/or Soda Ash, and Produce a Sodium Mineral Solution
Optionally Designate Selected Wellbores as Sodium Mineral Solution Wells
160
165
Optionally Produce Sodium Mineral Solution from The Sodium Mineral Solution Wells

FIG. 2

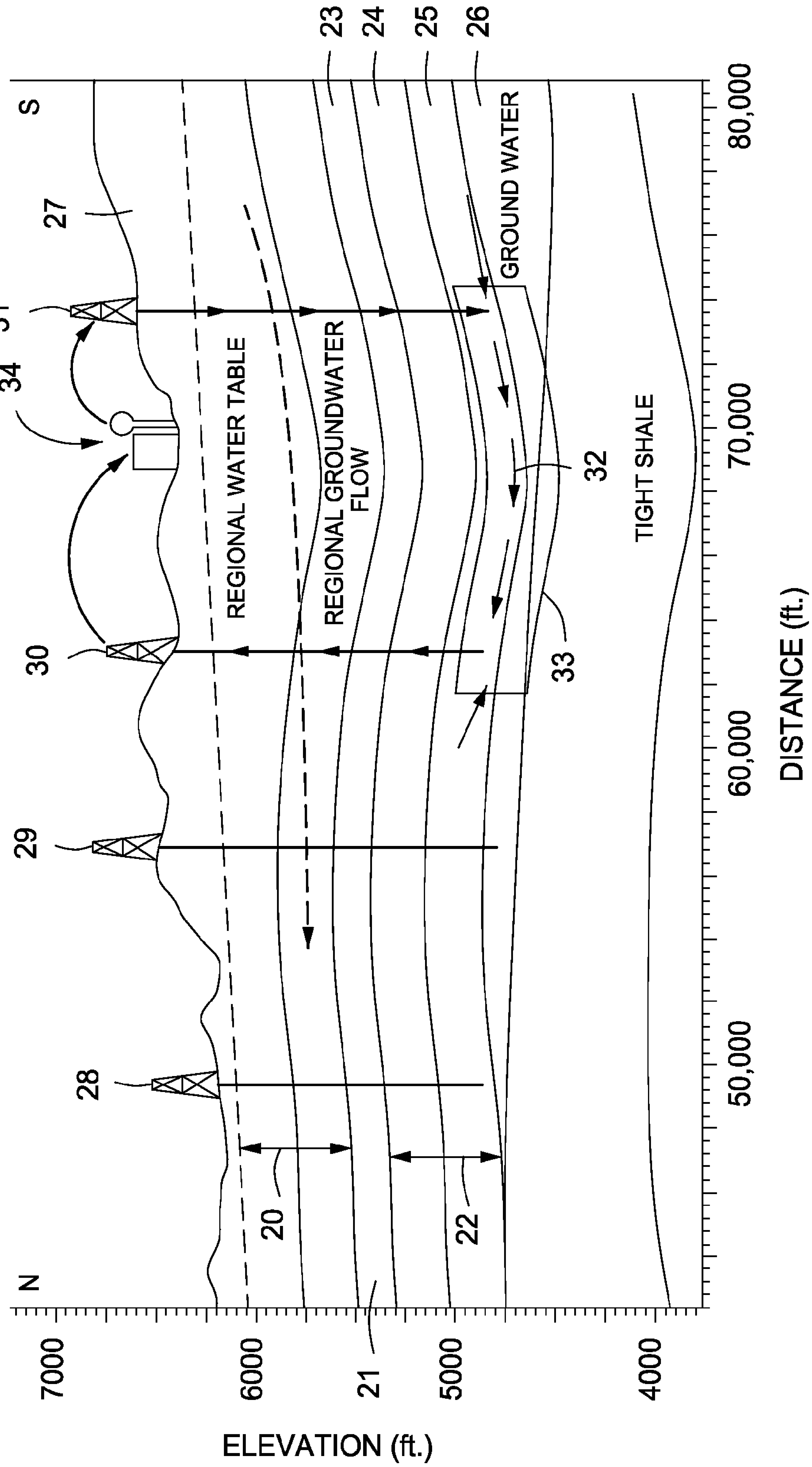

S
N
27
31
34
30
29
28
23
24
25
26
REGIONAL WATER TABLE
REGIONAL GROUNDWATER FLOW
GROUND WATER
TIGHT SHALE
32
33
20
21
22
7000
6000
5000
4000
ELEVATION (ft.)
50,000
60,000
70,000
80,000
DISTANCE (ft.)

FIG. 3

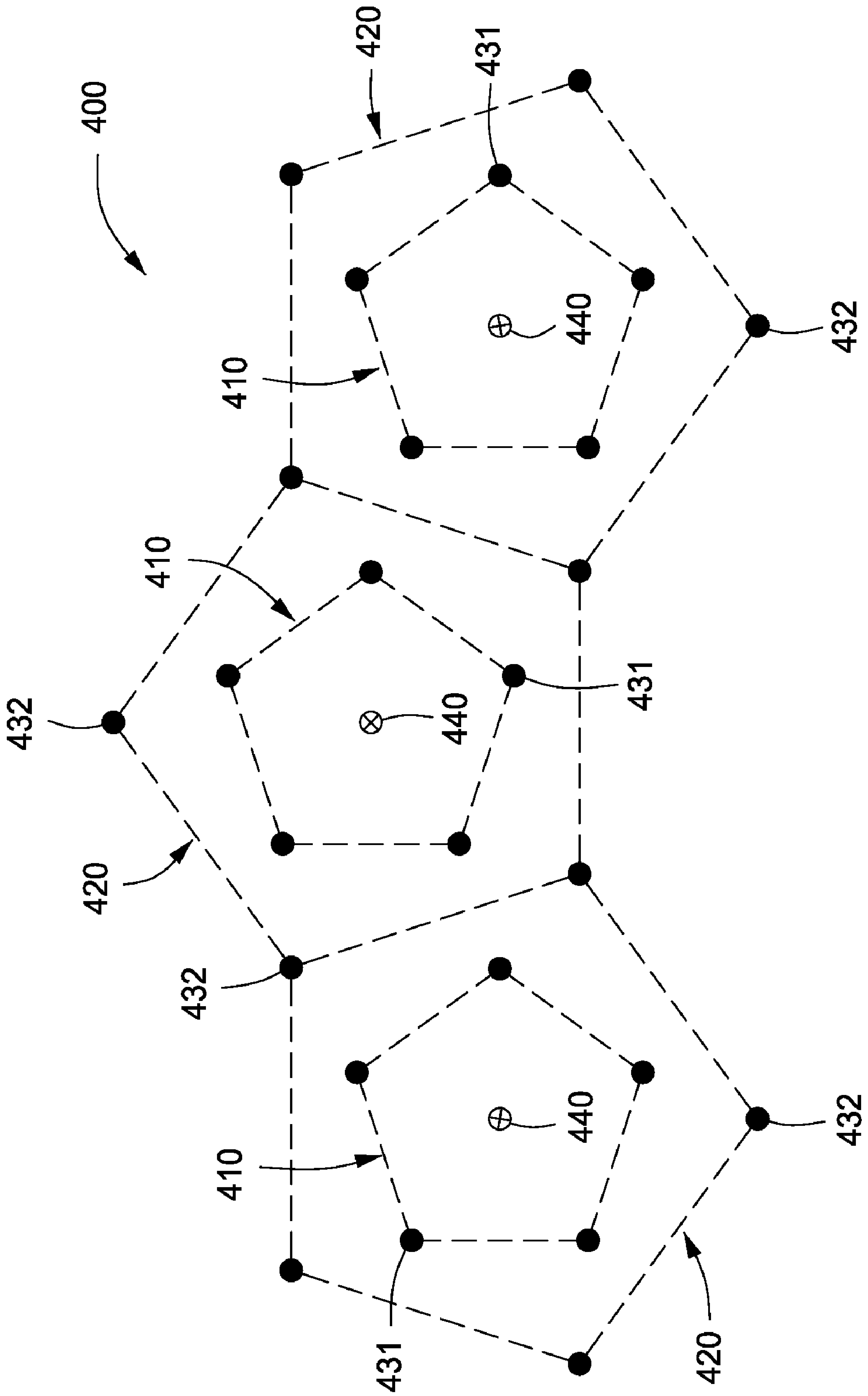

400
420
431
432
410
440
410
432
431
440
420
432
432
410
440
431
420

FIG. 4

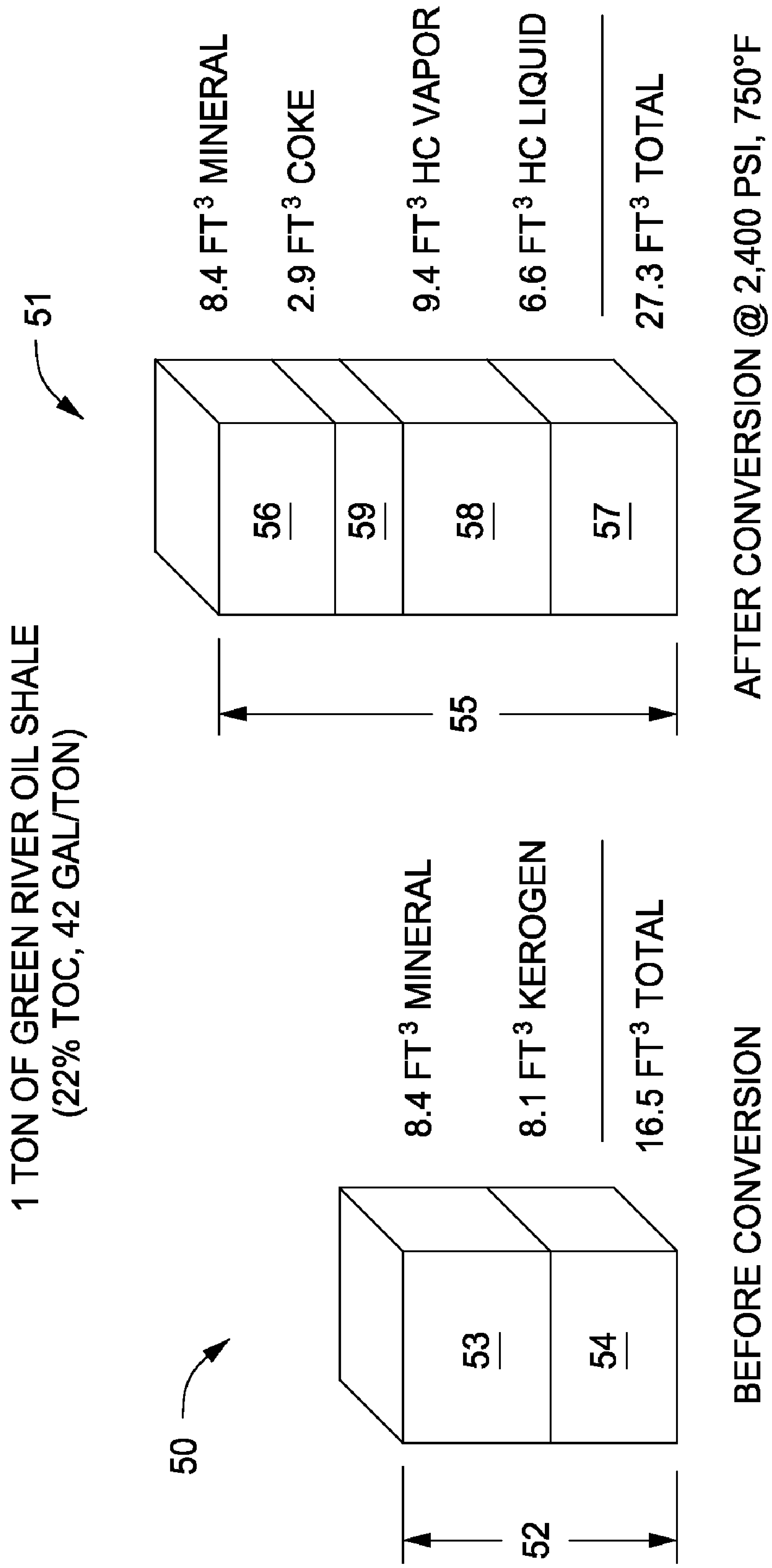

1 TON OF GREEN RIVER OIL SHALE
(22% TOC, 42 GAL/TON)
50
52
53
54
8.4 FT^3 MINERAL
8.1 FT^3 KEROGEN
16.5 FT^3 TOTAL
BEFORE CONVERSION
51
55
56
59
58
57
8.4 FT^3 MINERAL
2.9 FT^3 COKE
9.4 FT^3 HC VAPOR
6.6 FT^3 HC LIQUID
27.3 FT^3 TOTAL
AFTER CONVERSION @ 2,400 PSI, 750°F

FIG. 5

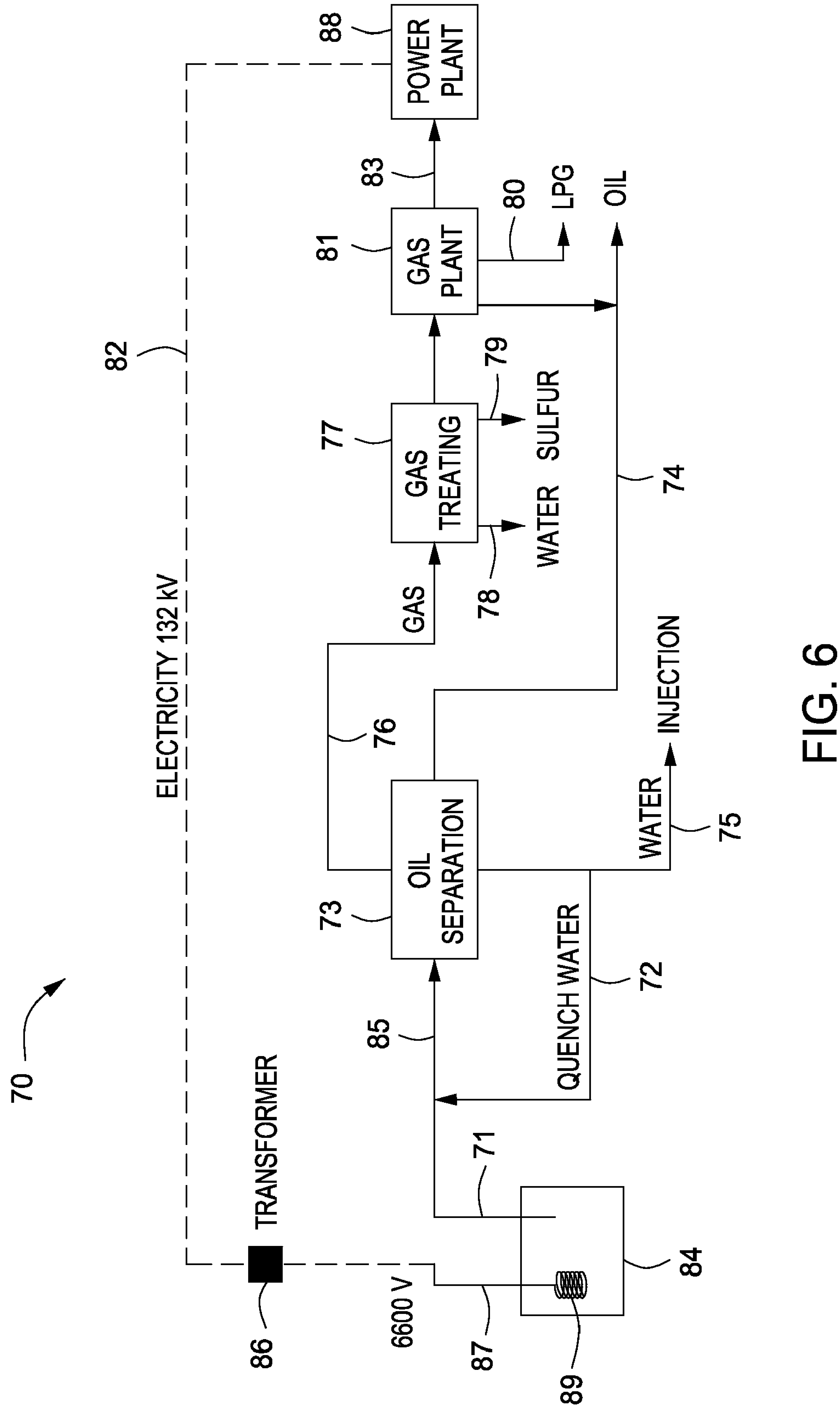

70
POWER PLANT
88
GAS PLANT
81
83
80
LPG
OIL
82
GAS TREATING
77
79
SULFUR
WATER
78
74
GAS
ELECTRICITY 132 kV
76
INJECTION
OIL SEPARATION
73
WATER
75
QUENCH WATER
72
85
TRANSFORMER
71
84
86
6600 V
87
89

FIG. 6

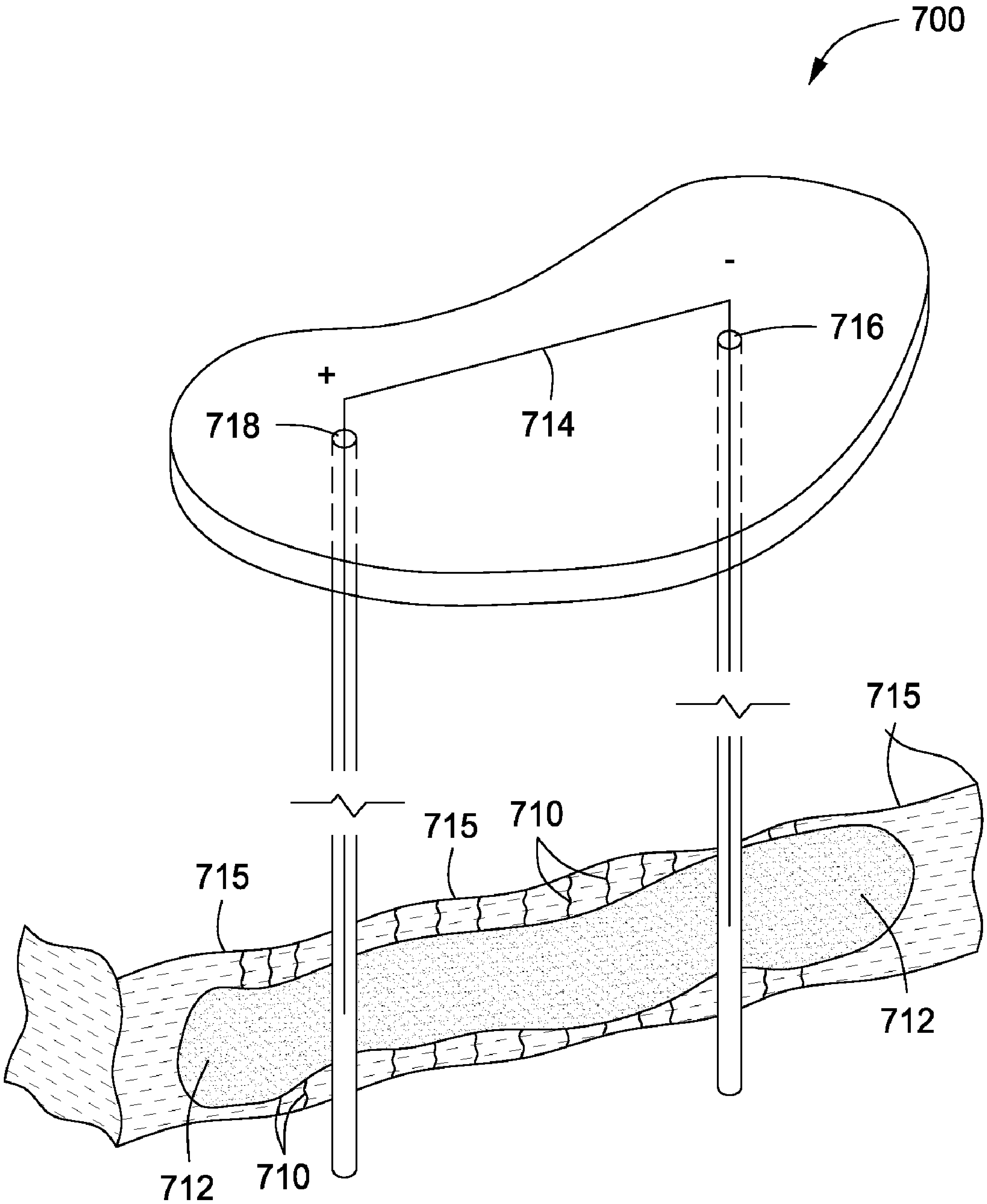


FIG. 7

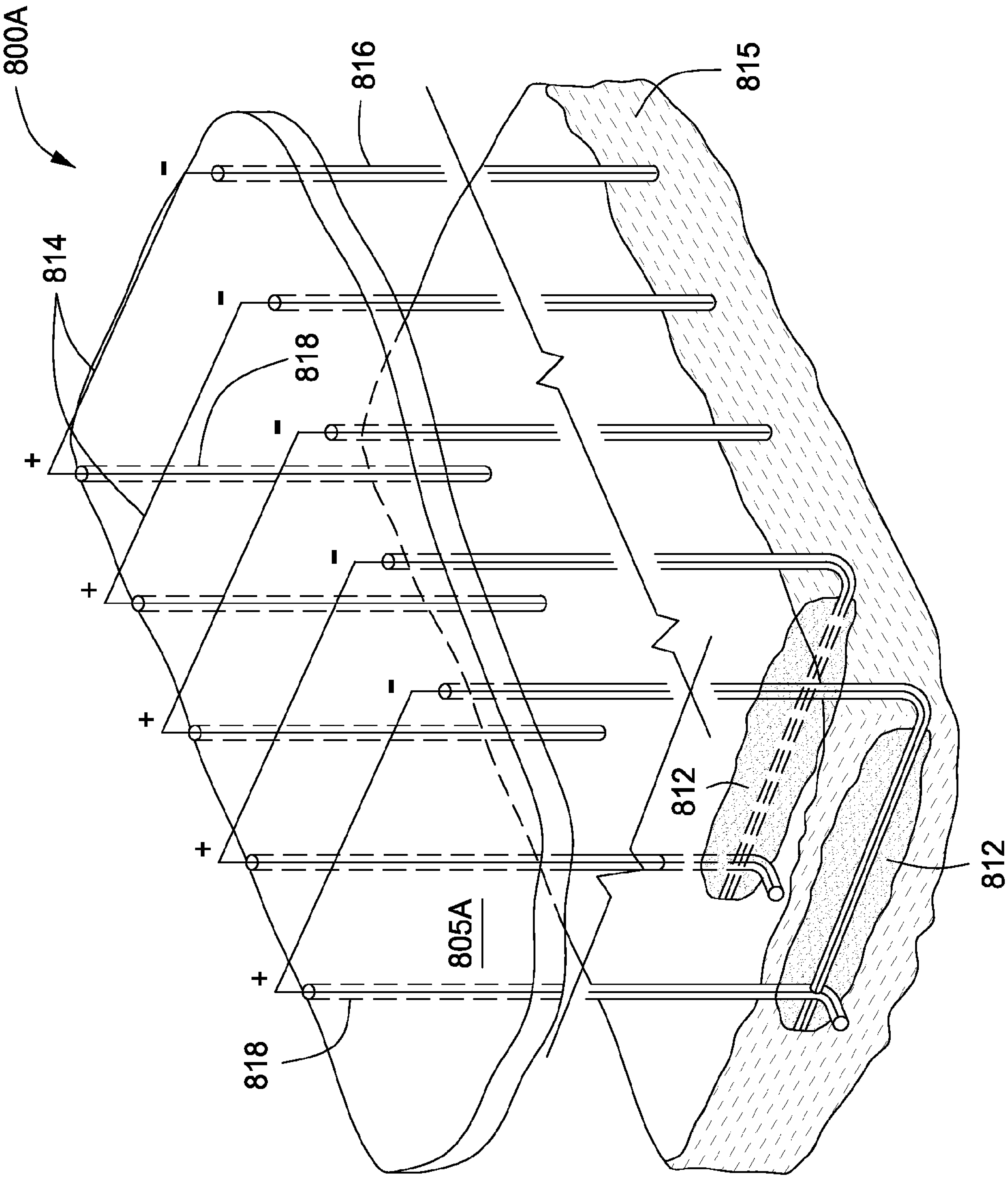


FIG. 8A

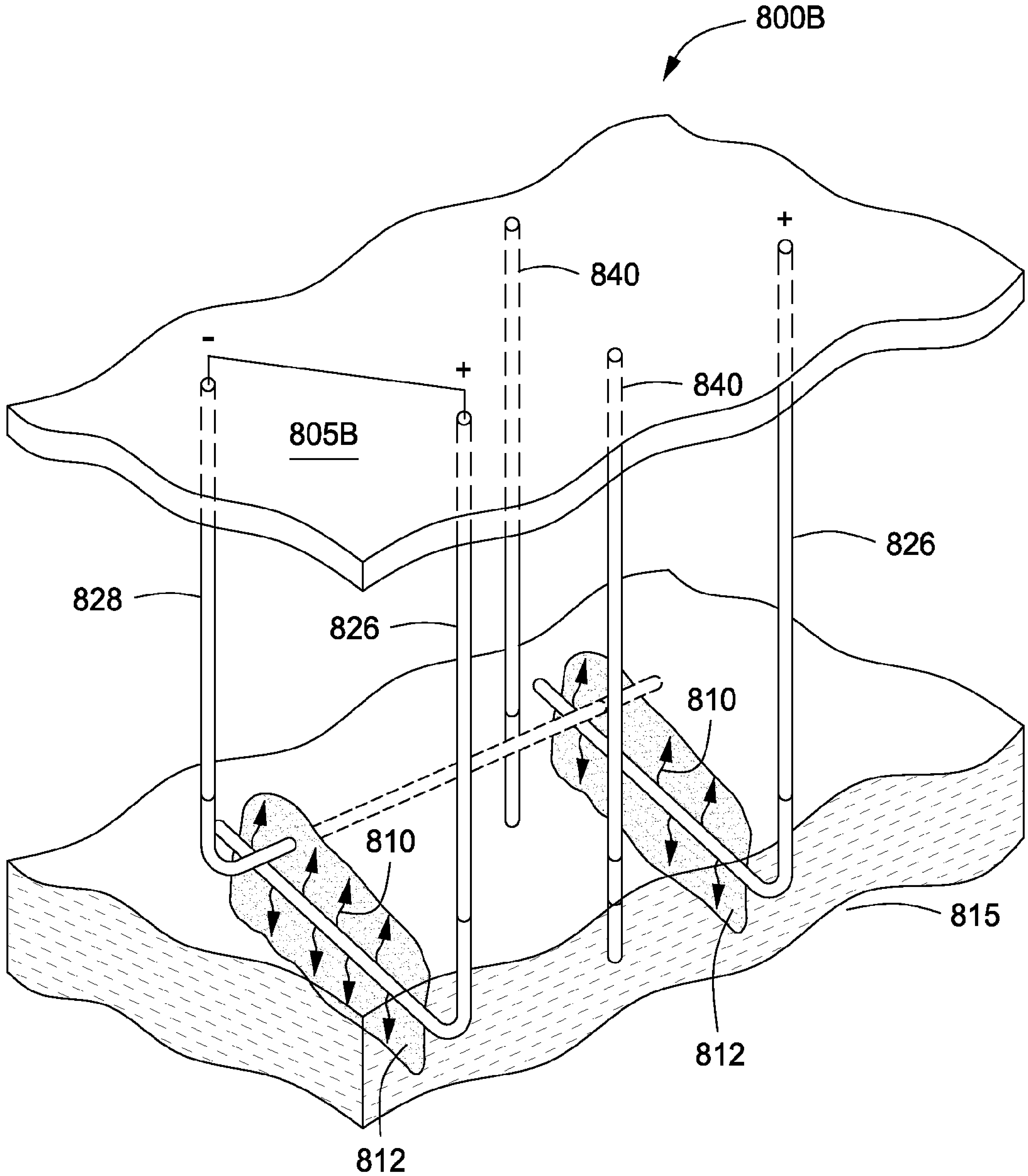


FIG. 8B

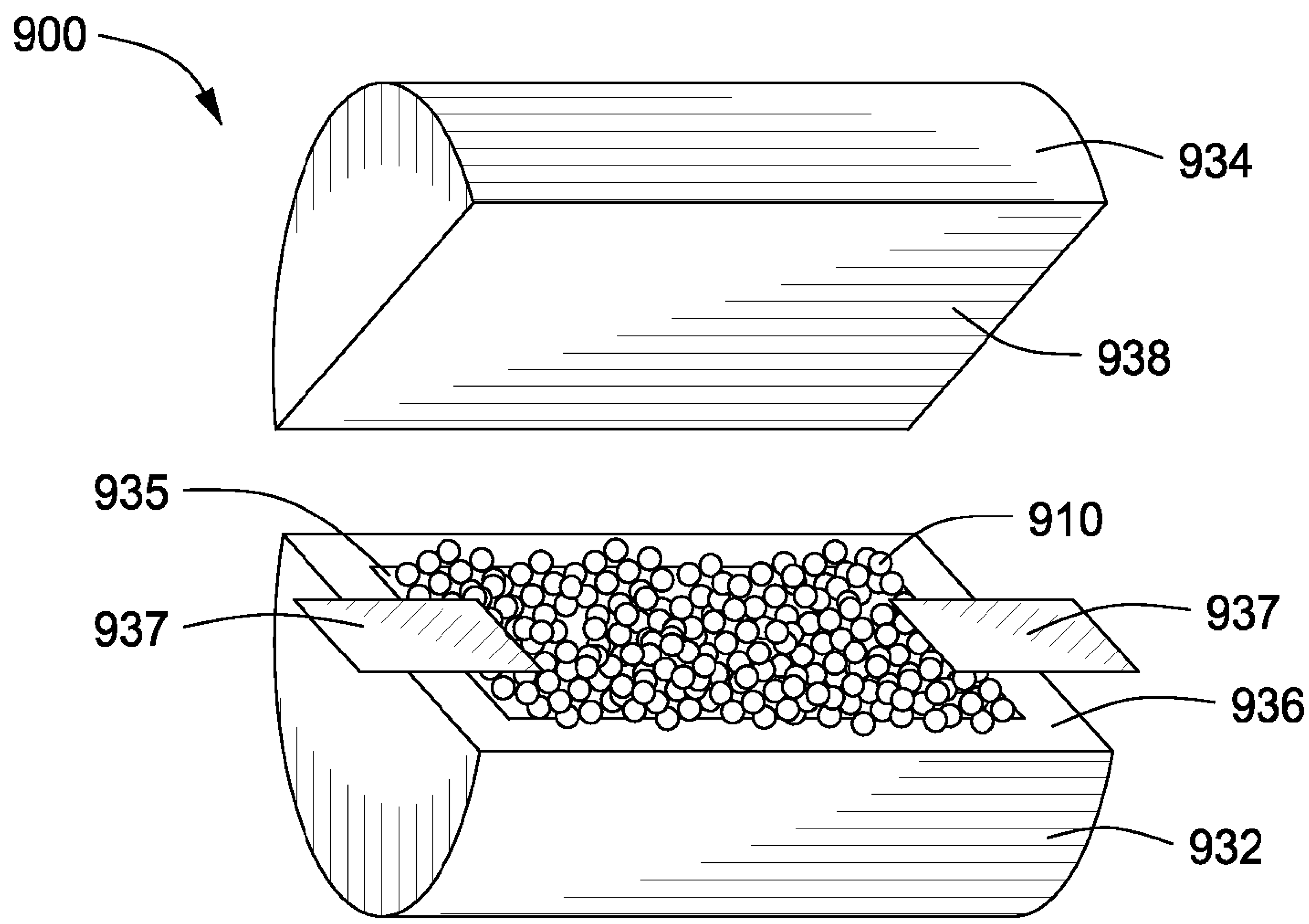


FIG. 9

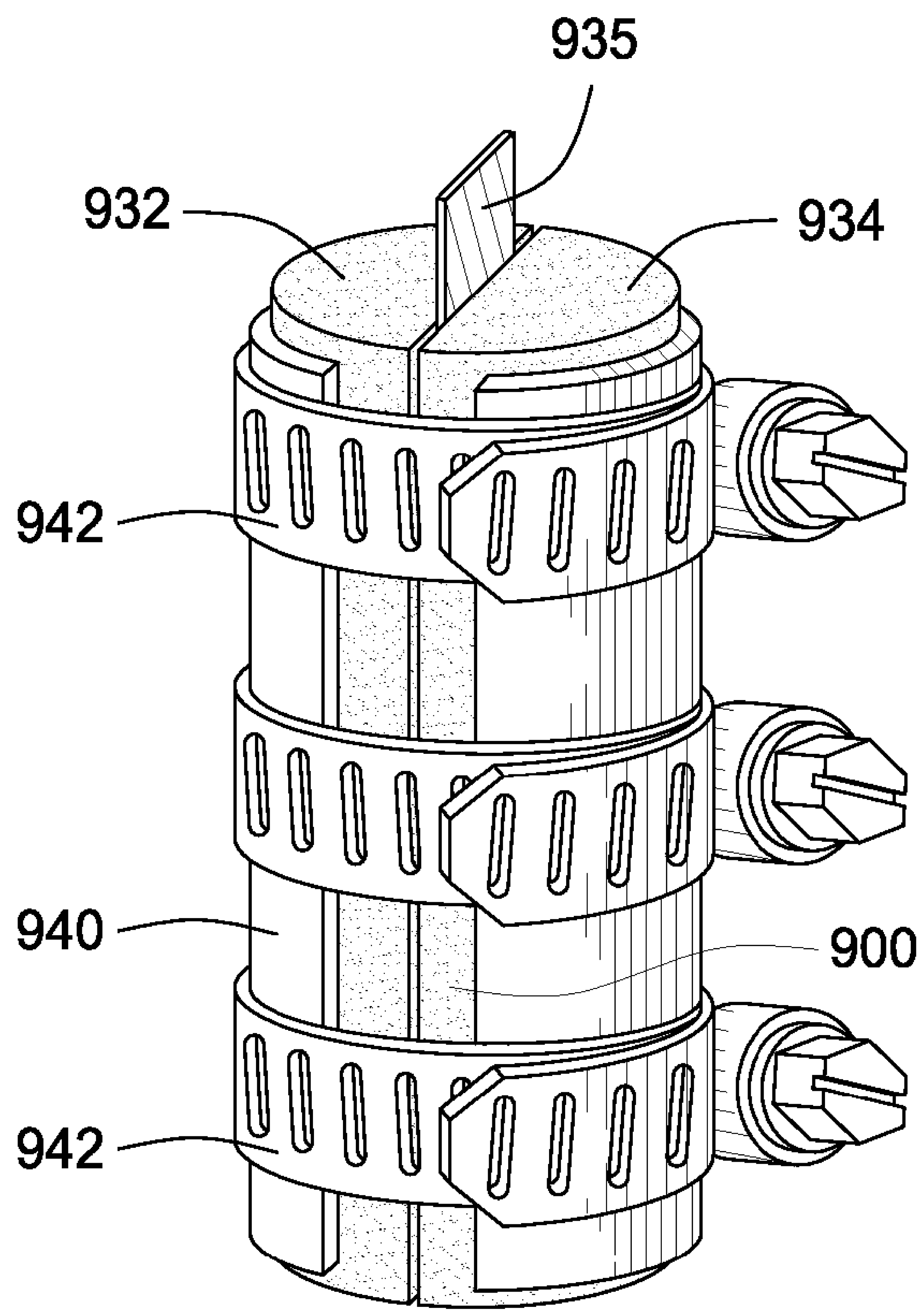


FIG. 10

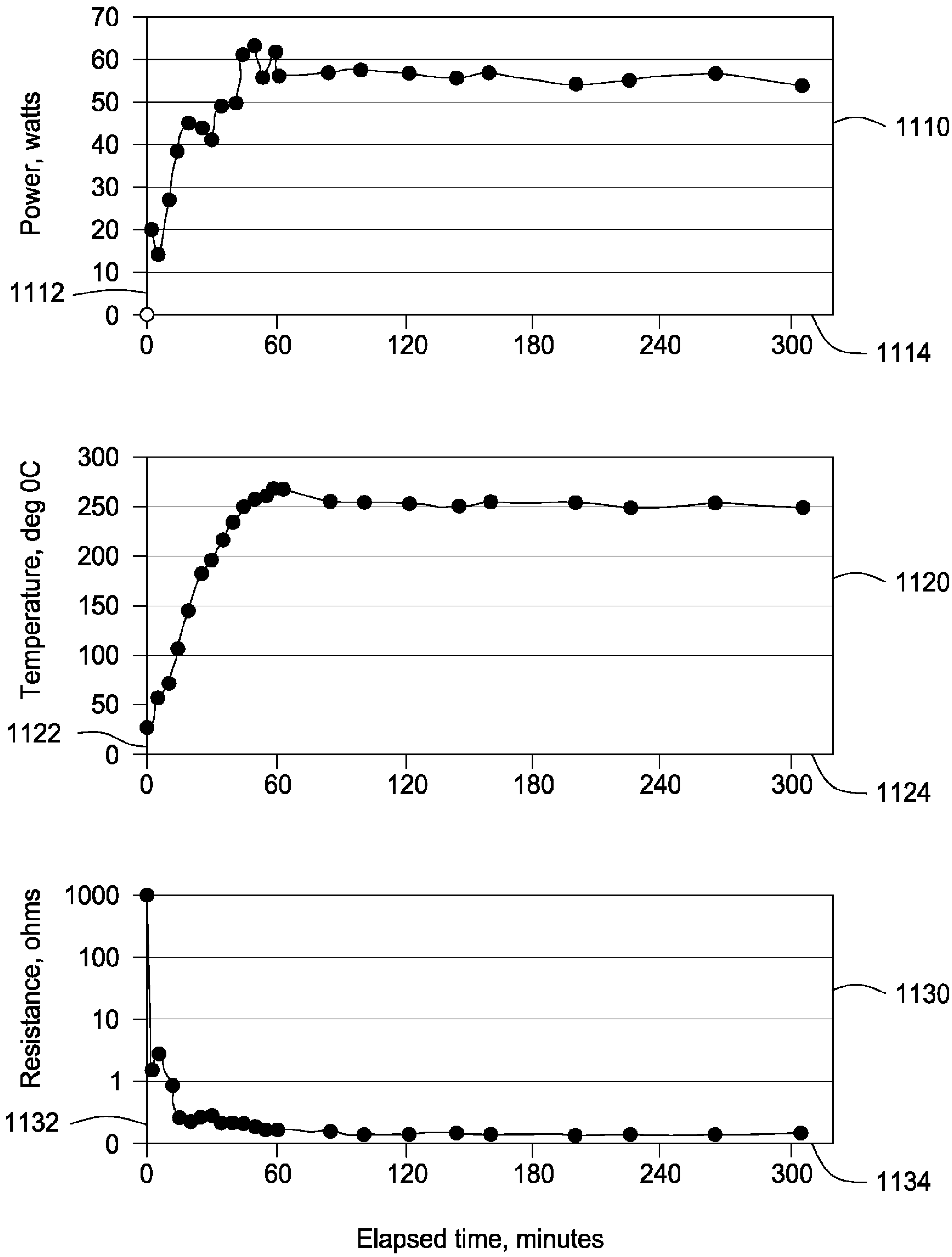

Power, watts
70
60
50
40
30
20
10
0
1110
1112
1114
Temperature, deg 0C
300
250
200
150
100
50
0
1120
1122
1124
Resistance, ohms
1000
100
10
1
0
1130
1132
1134
0
60
120
180
240
300
Elapsed time, minutes

FIG. 11

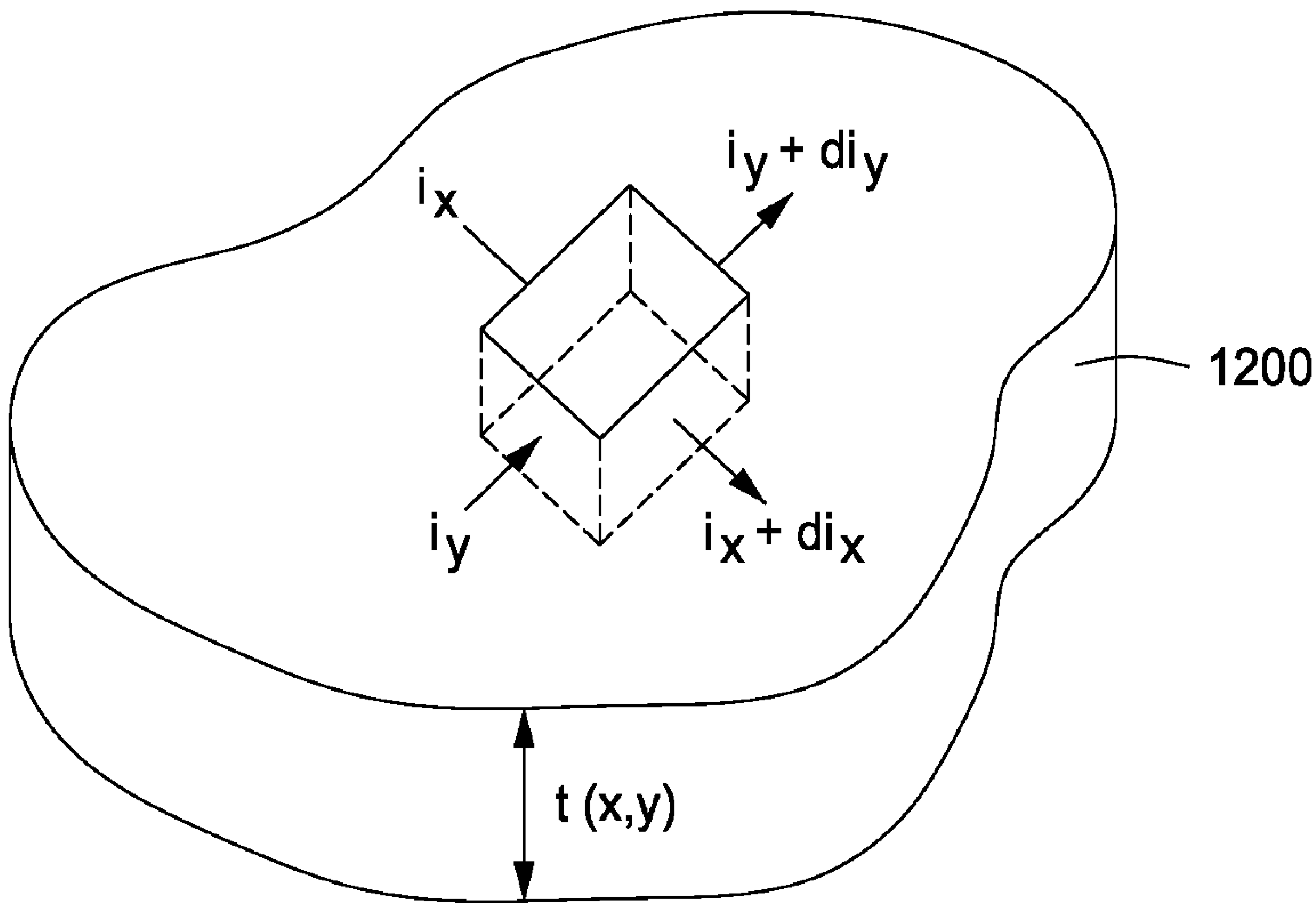
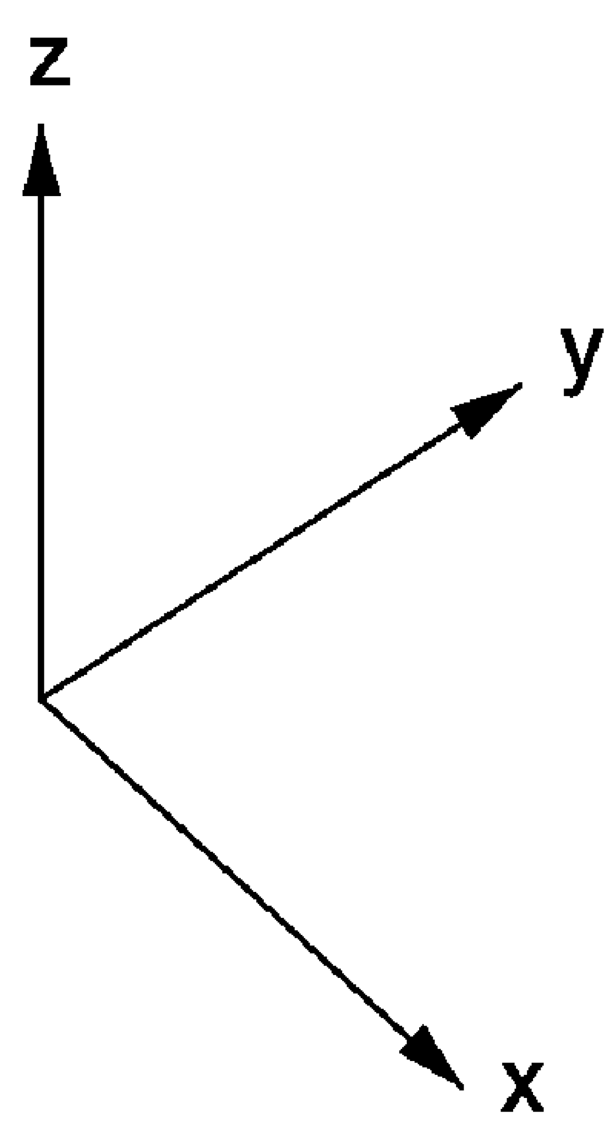


FIG. 12



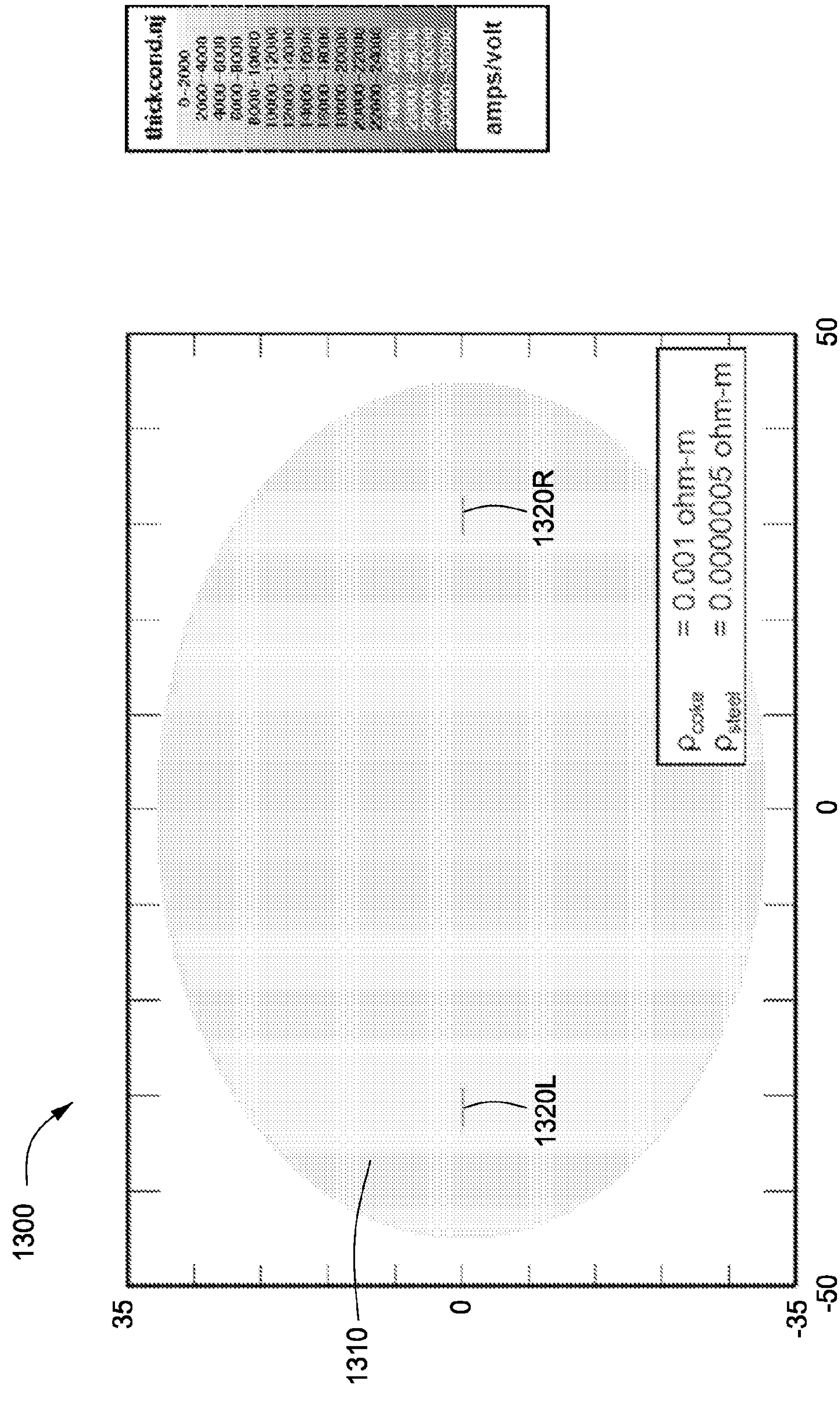
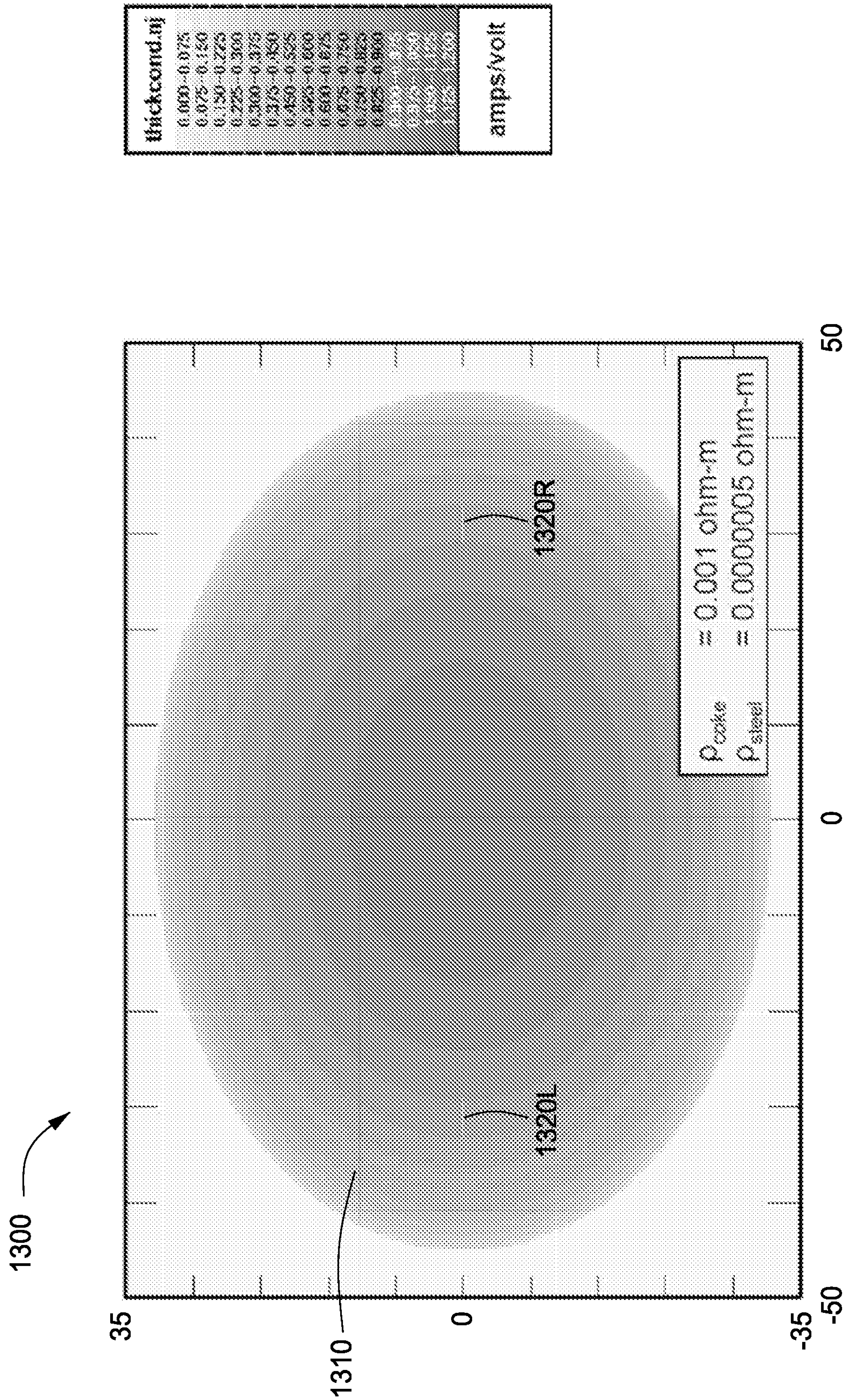
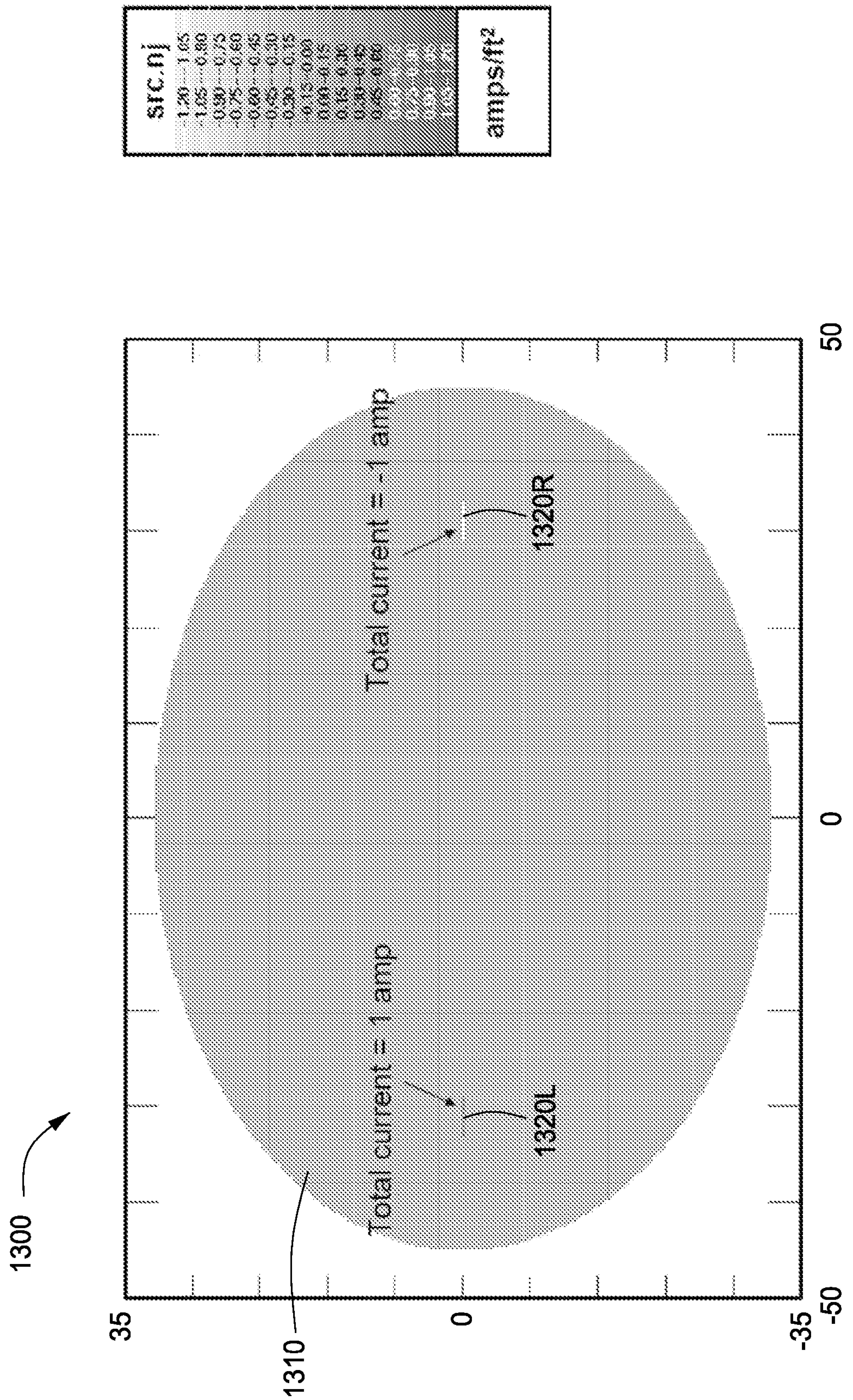

1300
1310
1320L
1320R
35
0
-35
-50
0
50
ρ_{coke} = 0.001 ohm-m
ρ_{steel} = 0.0000005 ohm-m
thickcond.nj
amps/volt

FIG. 13



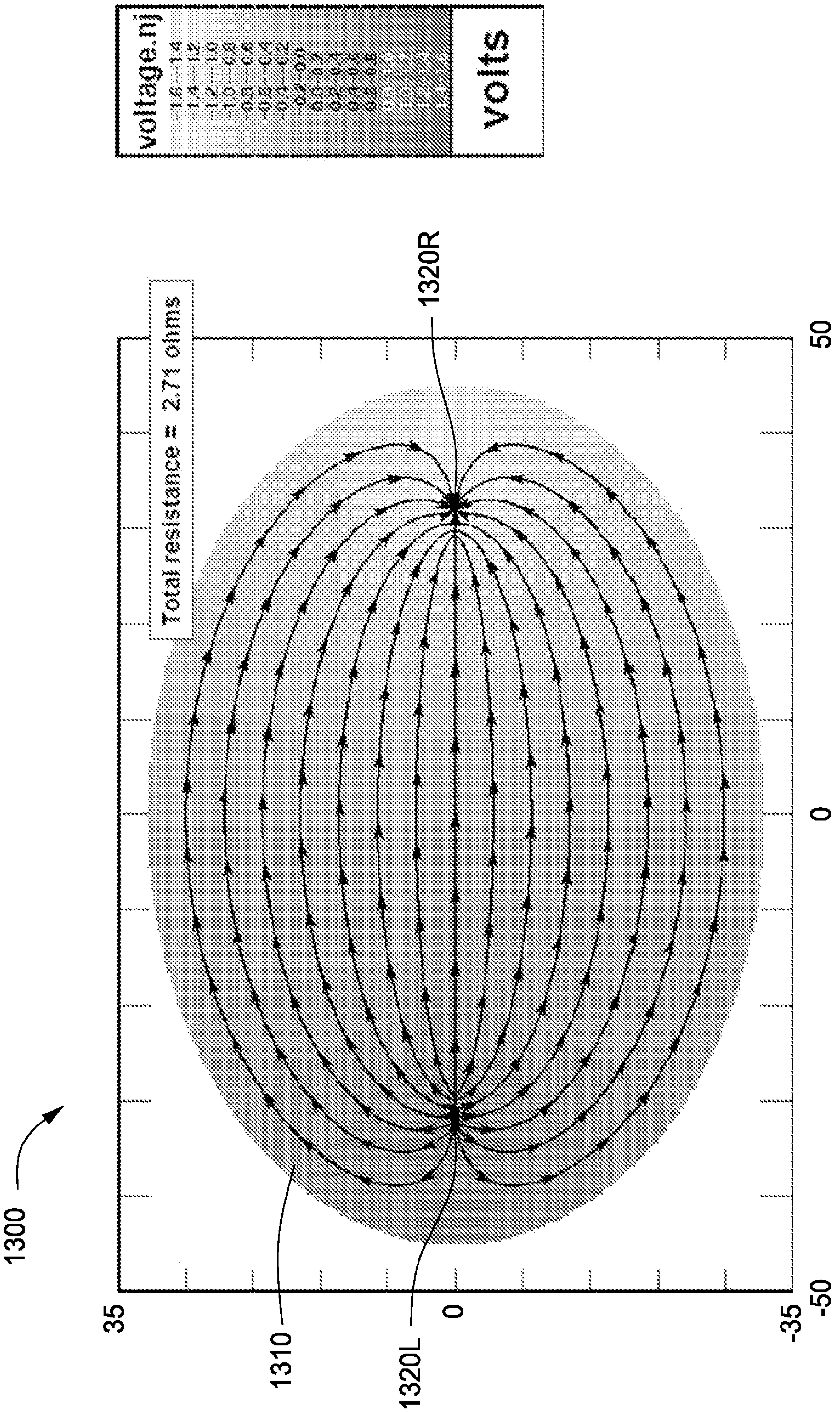
1300
1310
1320L
1320R
35
0
-35
-50
0
50
ρ_{coke} = 0.001 ohm-m
ρ_{steel} = 0.000005 ohm-m
thickcond.nj
0.000-0.075
0.075-0.150
0.150-0.225
0.225-0.300
0.300-0.375
0.375-0.450
0.450-0.525
0.525-0.600
0.600-0.675
0.675-0.750
0.750-0.825
0.825-0.900
amps/volt

FIG. 14



src.nj
amps/ft²
1300
1310
Total current = 1 amp
1320L
Total current = -1 amp
1320R
35
0
-35
-50
0
50

FIG. 15



voltage.nj
volts
Total resistance = 2.71 ohms
1300
1310
1320L
1320R
35
0
-35
-50
0
50

FIG. 16

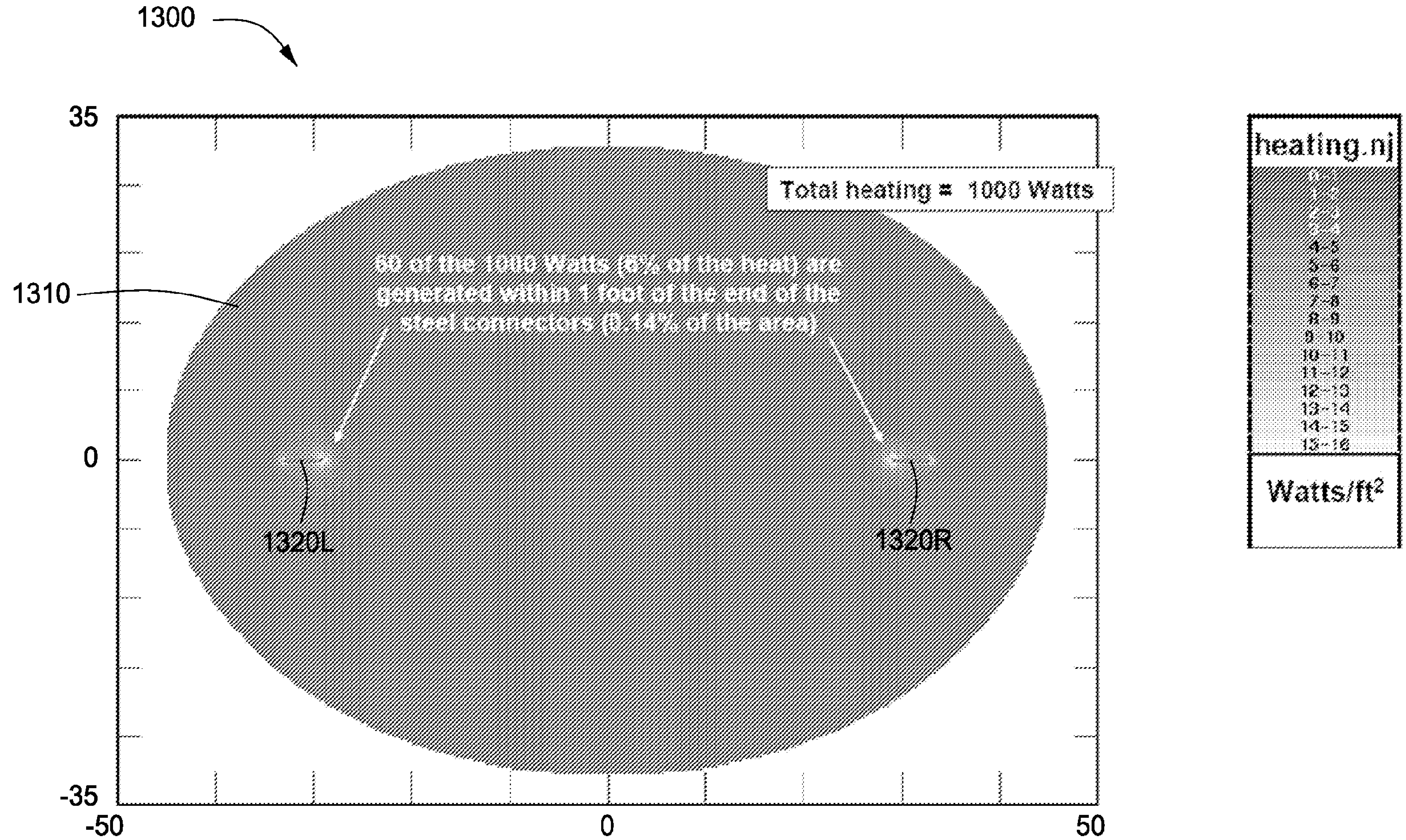

1300
1310
1320L
1320R
35
0
-35
-50
0
50
Total heating = 1000 Watts
60 of the 1000 Watts (6% of the heat) are generated within 1 foot of the end of the steel connectors (0.14% of the area)
heating.nj
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
14-15
15-16
Watts/ft²

FIG. 17

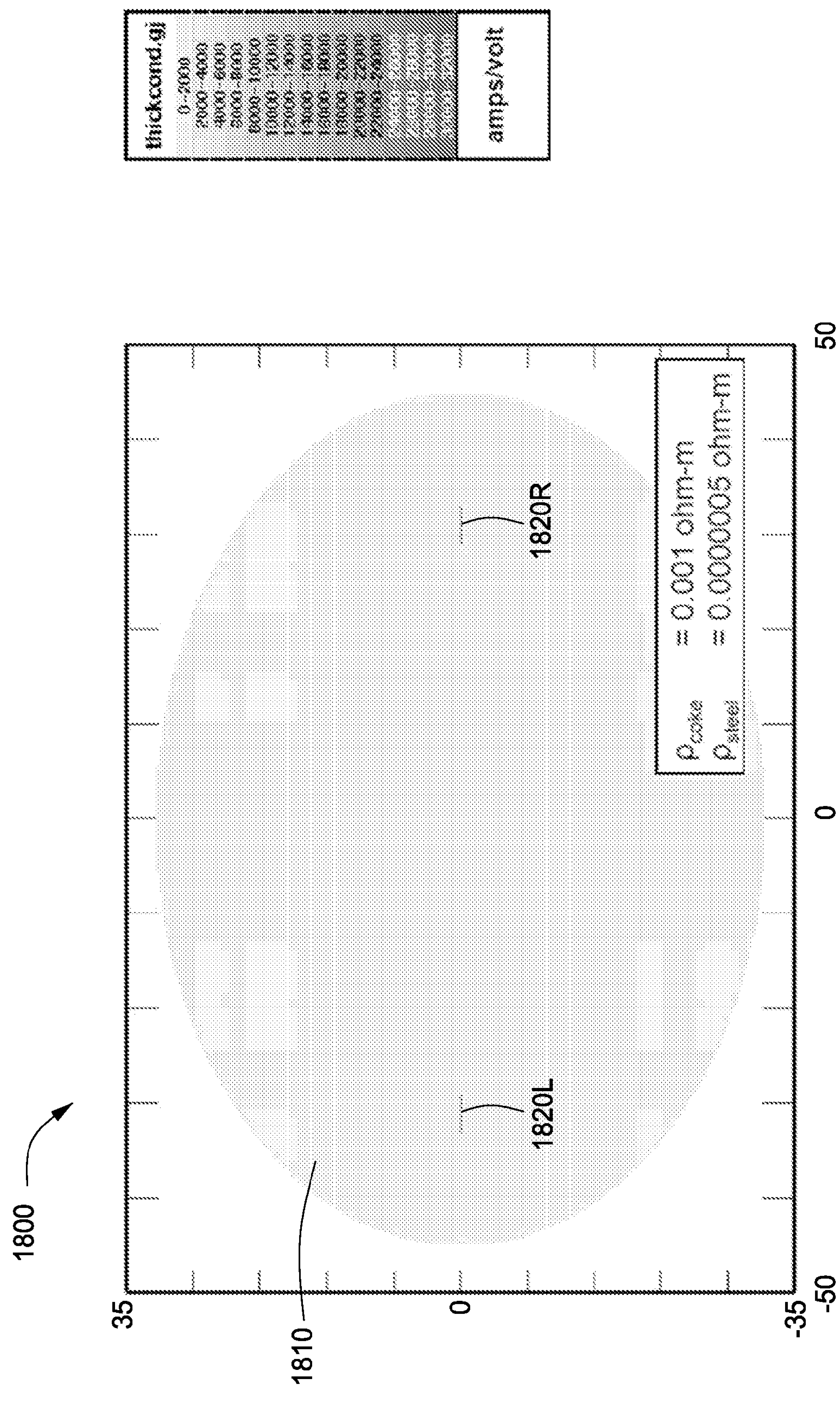
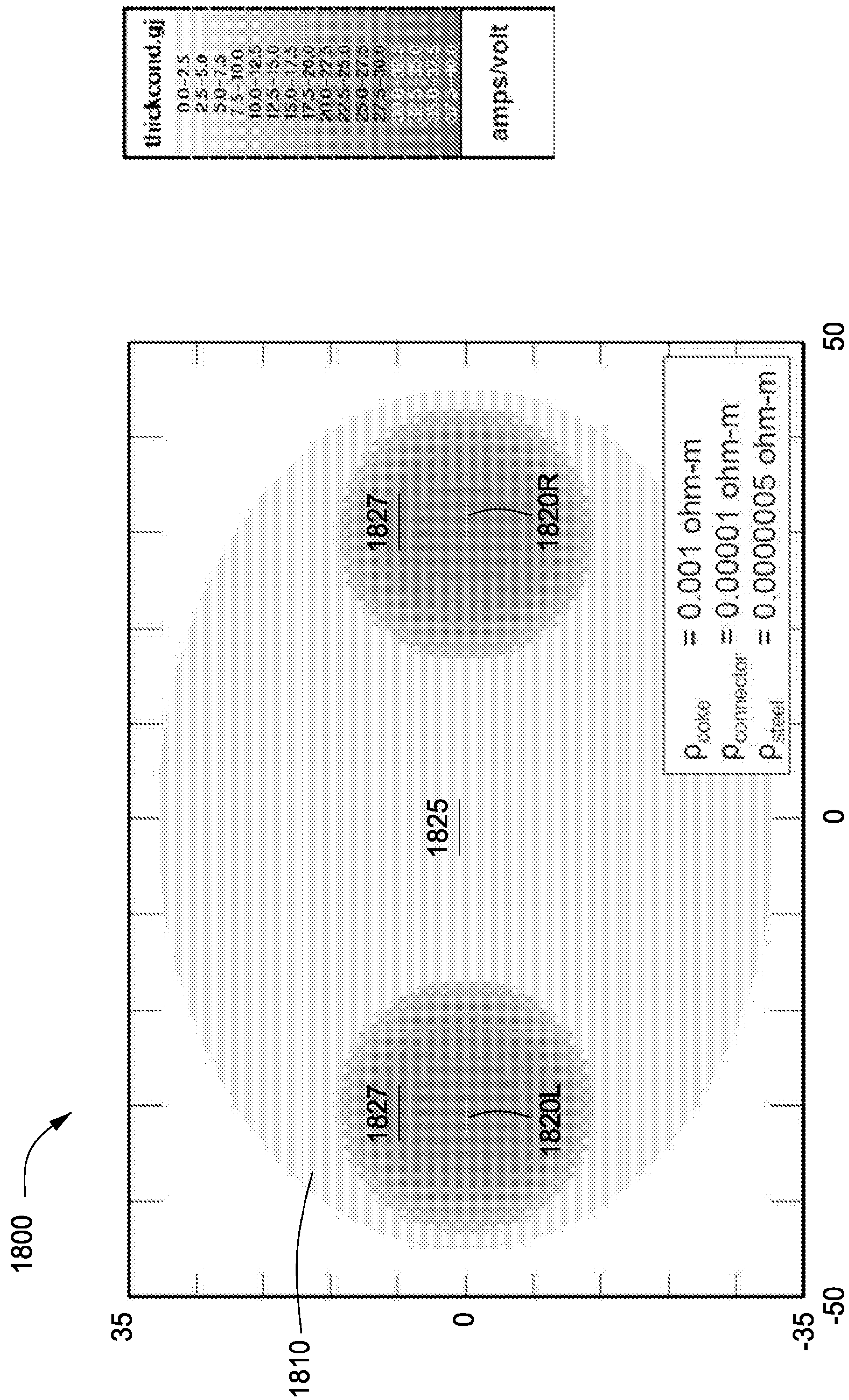

1800
1810
1820L
1820R
35
0
-35
-50
0
50
ρcoke = 0.001 ohm-m
ρsteel = 0.0000005 ohm-m
thickcond.gj
amps/volt

FIG. 18



thickcond.gj
amps/volt
1800
1810
1825
1827
1827
1820L
1820R
35
0
-35
-50
0
50
ρ_{coke} = 0.001 ohm-m
$\rho_{connector}$ = 0.00001 ohm-m
ρ_{steel} = 0.0000005 ohm-m

FIG. 19

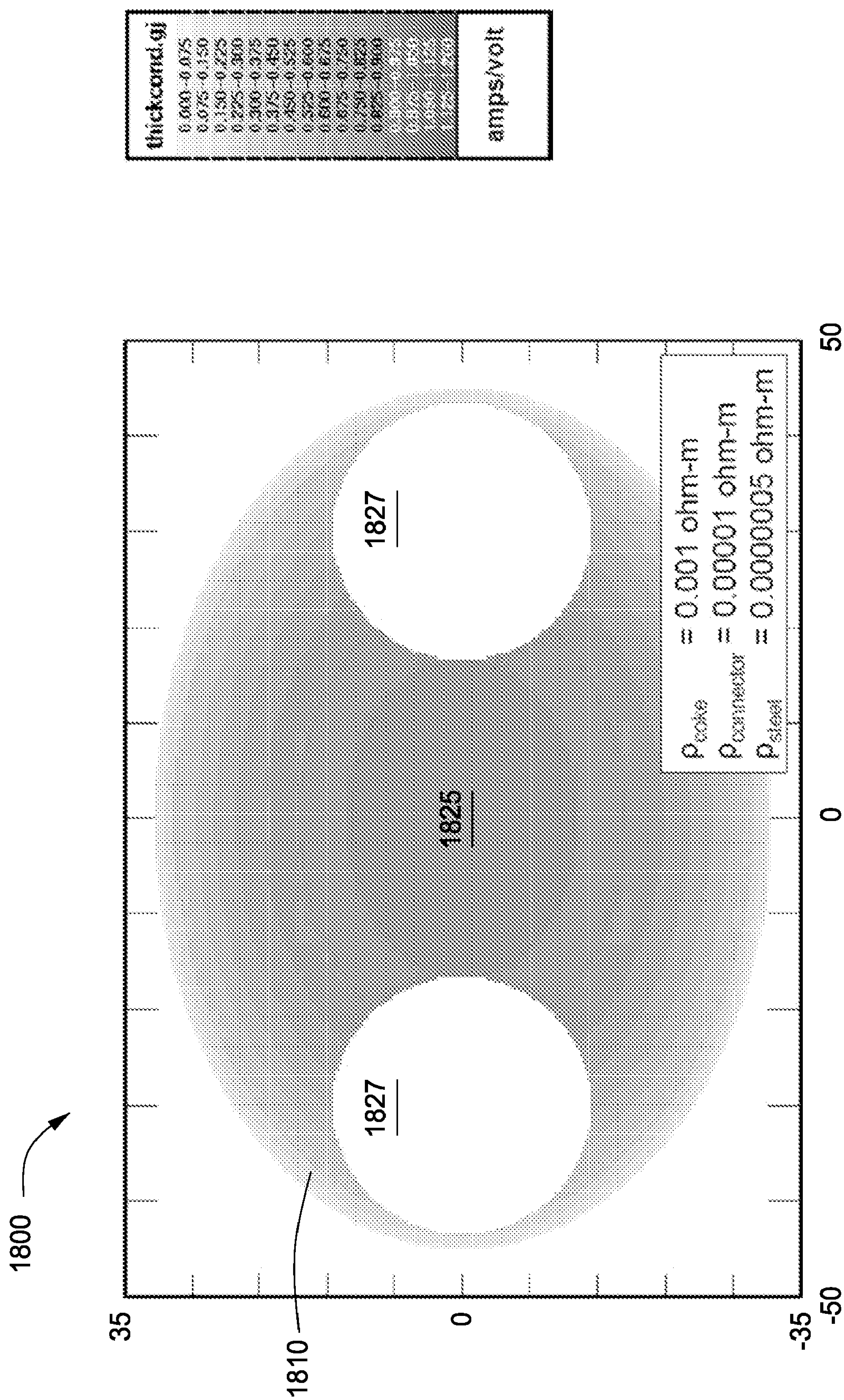

1800
1810
1825
1827
1827
35
0
-35
-50
0
50
ρ_{coke} = 0.001 ohm-m
$\rho_{connector}$ = 0.00001 ohm-m
ρ_{steel} = 0.0000005 ohm-m
thickcond.gj
amps/volt

FIG. 20

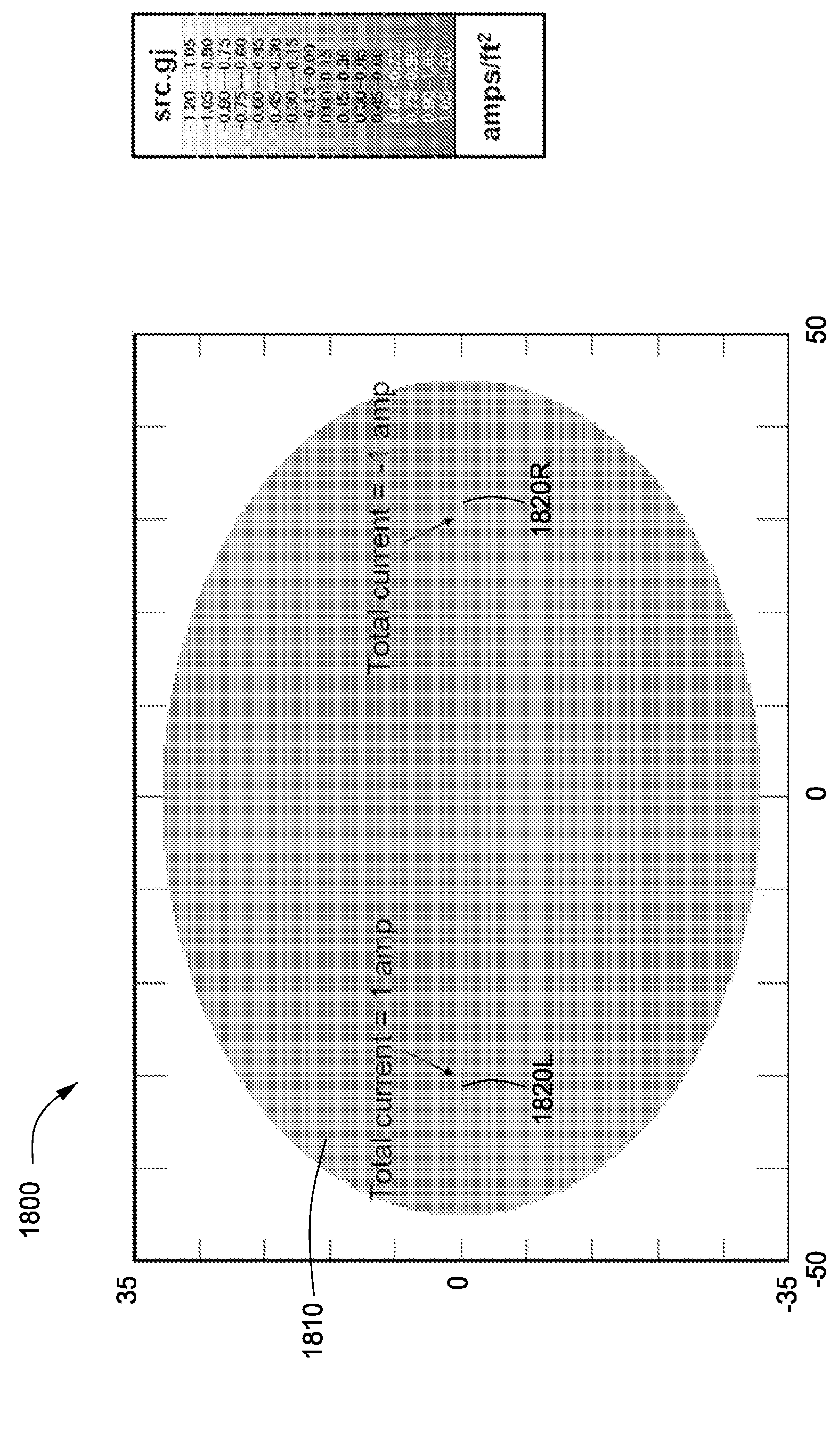

1800
1810
src.gj
amps/ft²
Total current = 1 amp
Total current = -1 amp
1820L
1820R
35
0
-35
-50
0
50

FIG. 21

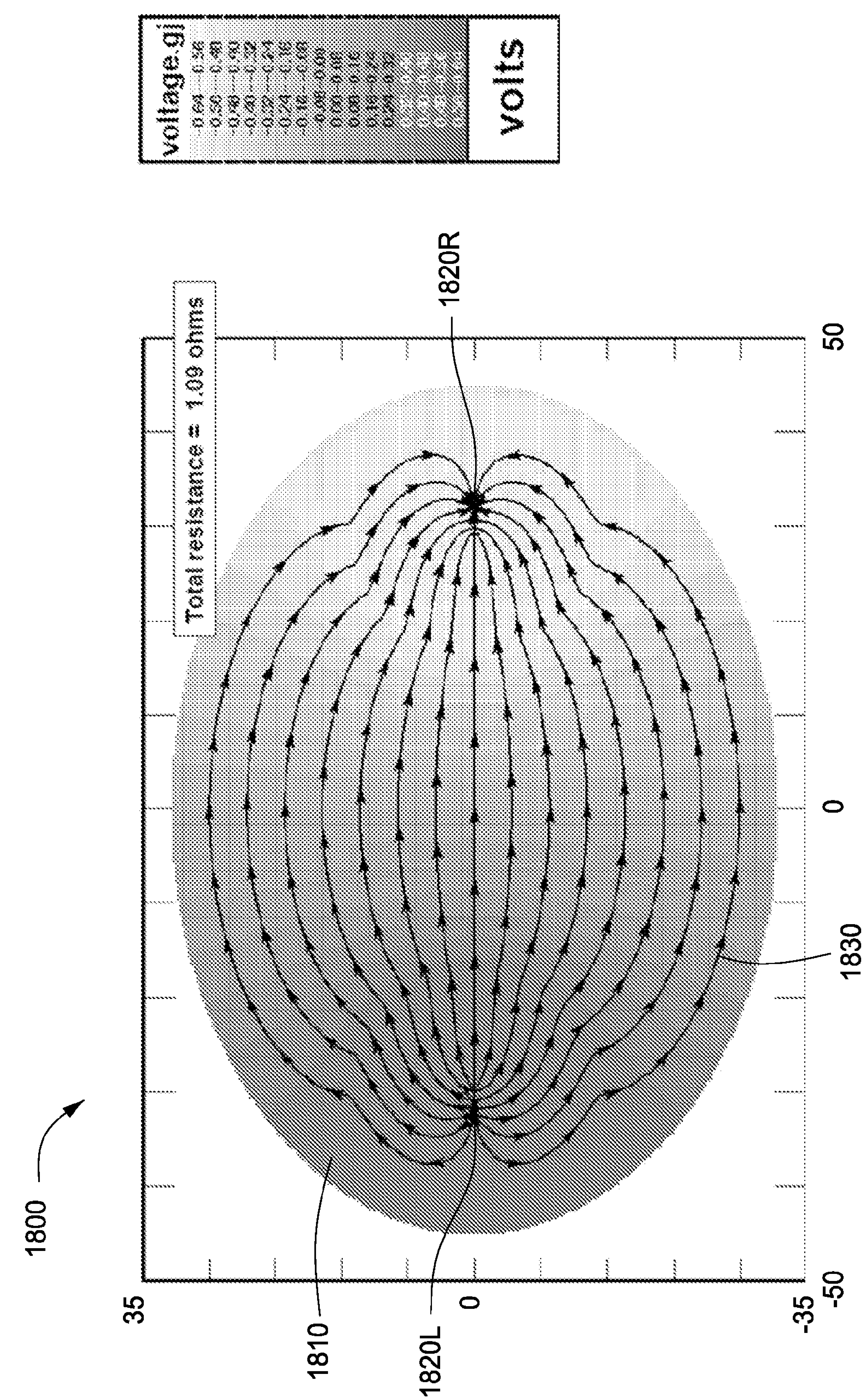

1800
voltage.gi
volts
Total resistance = 1.09 ohms
1820R
1830
1810
1820L
35
0
-35
-50
0
50

FIG. 22

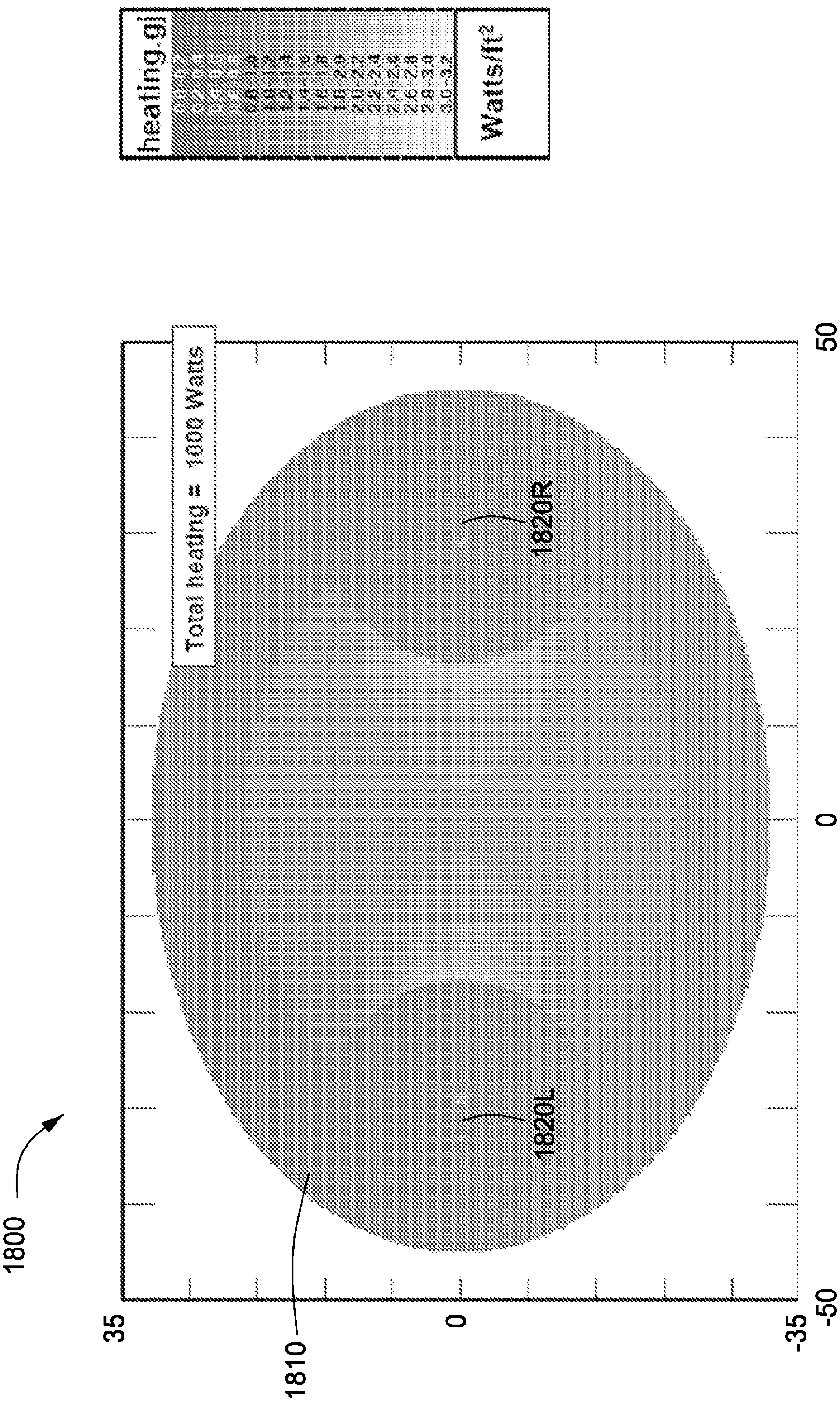

heating.gj
0.8-1.0
1.0-1.2
1.2-1.4
1.4-1.6
1.6-1.8
1.8-2.0
2.0-2.2
2.2-2.4
2.4-2.6
2.6-2.8
2.8-3.0
3.0-3.2
Watts/ft²
Total heating = 1000 Watts
1800
1810
1820L
1820R
35
0
-35
-50
0
50

FIG. 23

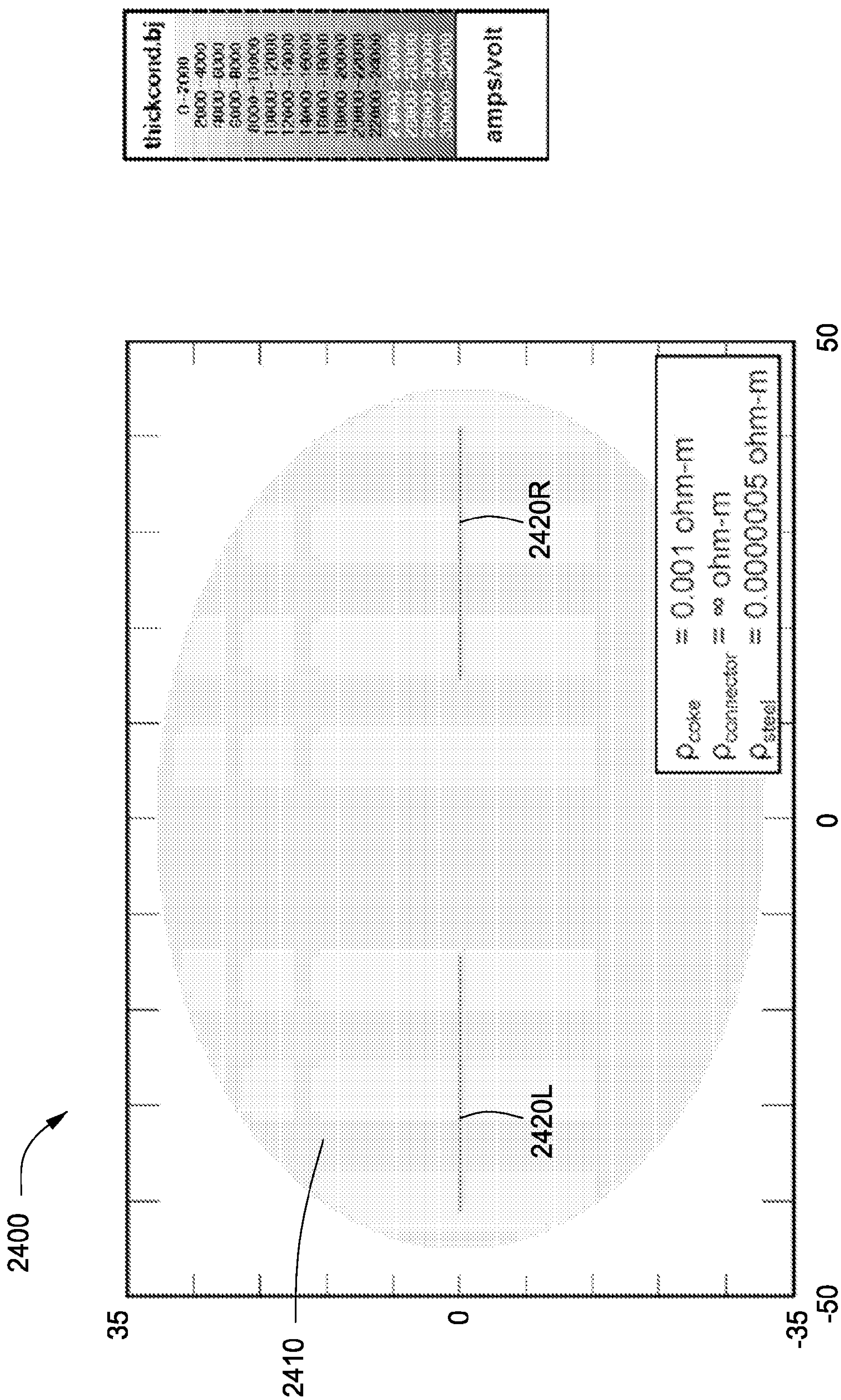

2400
2410
2420L
2420R
thickcond.bj
amps/volt
ρ_{coke} = 0.001 ohm-m
$\rho_{connector}$ = ∞ ohm-m
ρ_{steel} = 0.0000005 ohm-m
35
0
-35
-50
0
50

FIG. 24

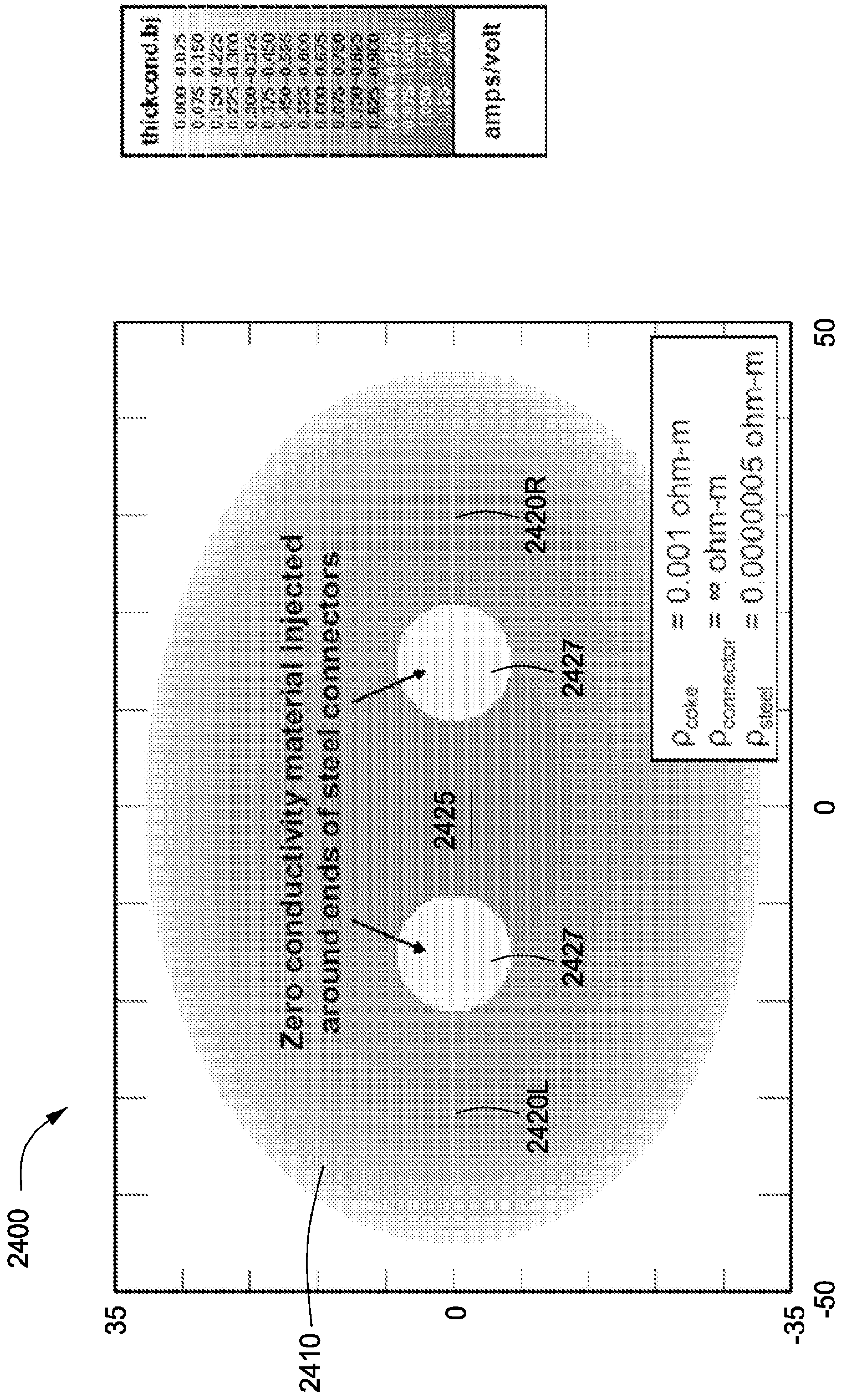
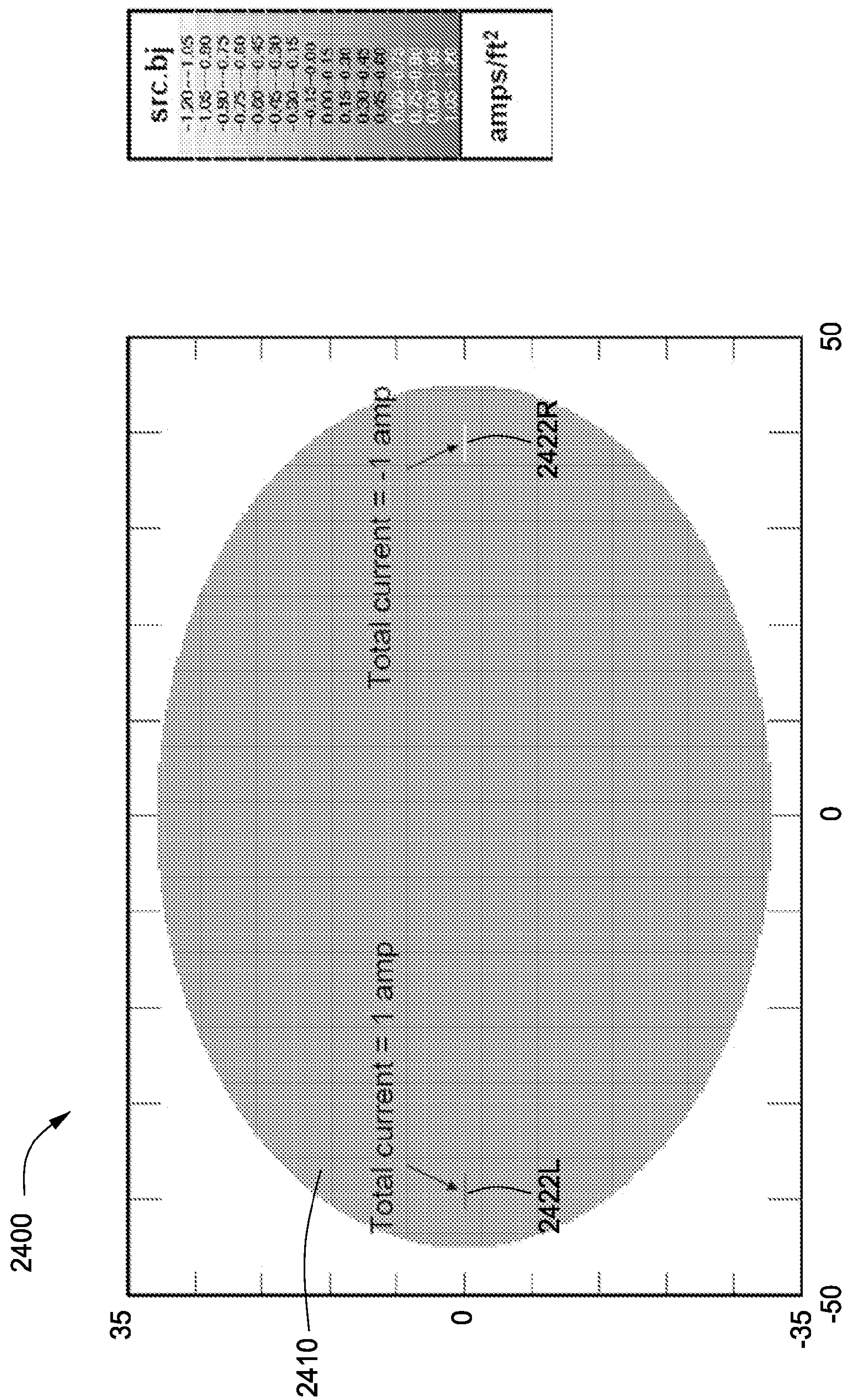

thickcond.bj
amps/volt
2400
2410
2420L
2420R
2425
2427
2427
Zero conductivity material injected around ends of steel connectors
ρ_{coke} = 0.001 ohm-m
$\rho_{connector}$ = ∞ ohm-m
ρ_{steel} = 0.000005 ohm-m
35
0
-35
-50
0
50

FIG. 25



2400
2410
src.bj
amps/ft2
35
0
-35
-50
0
50
Total current = 1 amp
Total current = -1 amp
2422L
2422R

FIG. 26

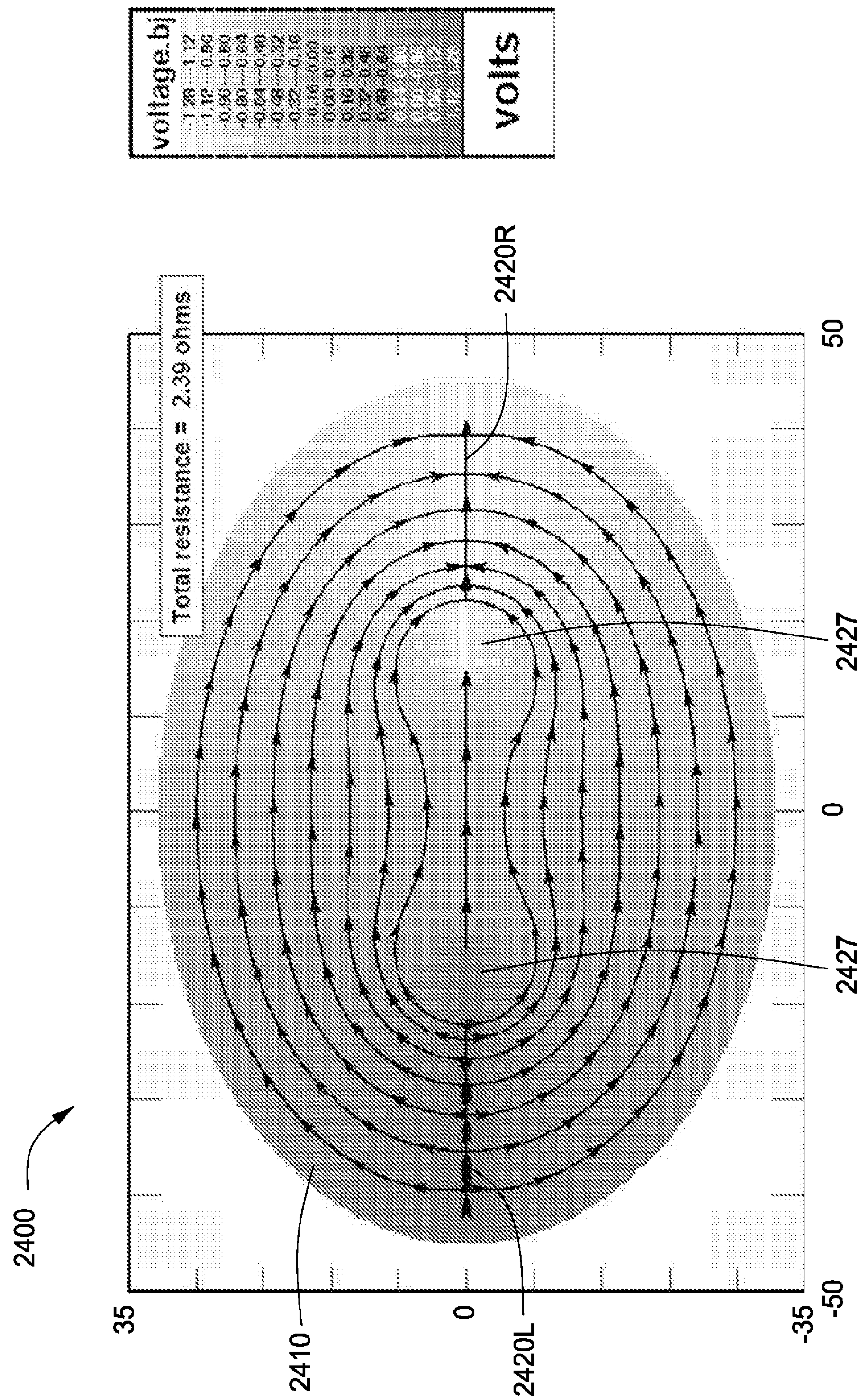

2400
voltage.bj
volts
Total resistance = 2.39 ohms
2420R
2427
2427
2410
2420L
35
0
-35
-50
0
50

FIG. 27

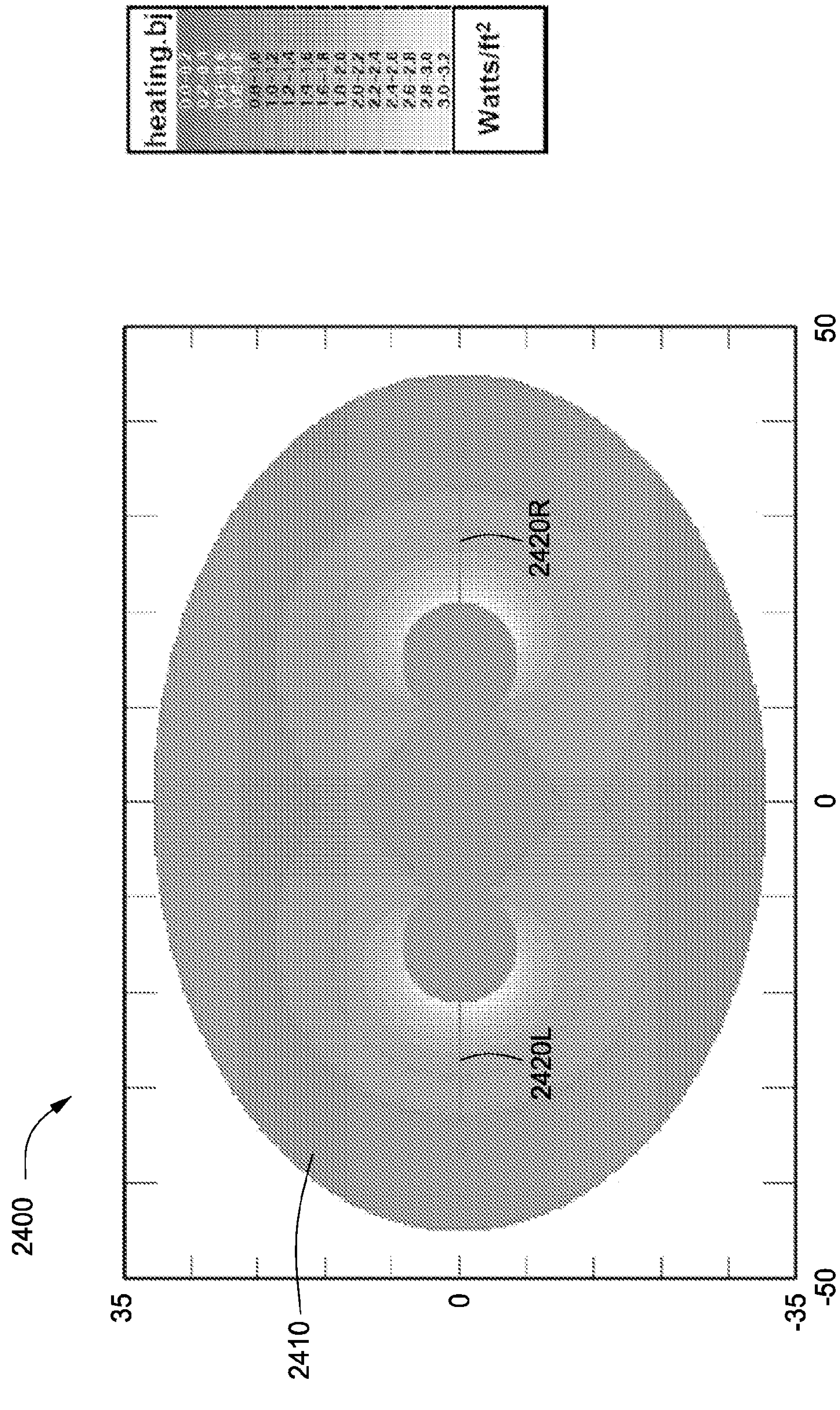


FIG. 28

ELECTRICALLY CONDUCTIVE METHODS FOR HEATING A SUBSURFACE FORMATION TO CONVERT ORGANIC MATTER INTO HYDROCARBON FLUIDS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application 61/109,369 filed 29 Oct. 2008 entitled ELECTRICALLY CONDUCTIVE METHODS FOR HEATING A SUBSURFACE FORMATION TO CONVERT ORGANIC MATTER INTO HYDROCARBON FLUIDS, the entirety of which is incorporated by reference herein. This application claims the benefit of pending U.S. non-provisional patent application Ser. No. 12/074,899, attorney Docket Number 2007EM026, which was filed on Mar. 7, 2008 and which is entitled “Granular Electrical Connections for In Situ Formation Heating” and is incorporated herein in its entirety by reference. U.S. application Ser. No. 12/074,899 in turn claims the benefit of pending U.S. provisional patent Application No. 60/919,391, which was filed on Mar. 22, 2007, which is also entitled “Granular Electrical Connections for In Situ Formation Heating,” and is incorporated herein in its entirety by reference.

BACKGROUND

[0002] 1. Technical Field

[0003] The present invention relates to the field of hydrocarbon recovery from subsurface formations. More specifically, the present invention relates to the in situ recovery of hydrocarbon fluids from organic-rich rock formations including, for example, oil shale formations, coal formations and tar sands formations. The present invention also relates to methods for heating a subsurface formation using electrical energy.

[0004] 2. Discussion of Technology

[0005] Certain geological formations are known to contain an organic matter known as “kerogen.” Kerogen is a solid, carbonaceous material. When kerogen is imbedded in rock formations, the mixture is referred to as oil shale. This is true whether or not the mineral is, in fact, technically shale, that is, a rock formed from compacted clay.

[0006] Kerogen is subject to decomposing upon exposure to heat over a period of time. Upon heating, kerogen molecularly decomposes to produce oil, gas, and carbonaceous coke. Small amounts of water may also be generated. The oil, gas and water fluids become mobile within the rock matrix, while the carbonaceous coke remains essentially immobile.

[0007] Oil shale formations are found in various areas world-wide, including the United States. Such formations are notably found in Wyoming, Colorado, and Utah. Oil shale formations tend to reside at relatively shallow depths and are often characterized by limited permeability. Some consider oil shale formations to be hydrocarbon deposits which have not yet experienced the years of heat and pressure thought to be required to create conventional oil and gas reserves.

[0008] The decomposition rate of kerogen to produce mobile hydrocarbons is temperature dependent. Temperatures generally in excess of 270° C. (518° F.) over the course of many months may be required for substantial conversion. At higher temperatures substantial conversion may occur within shorter times. When kerogen is heated to the necessary temperature, chemical reactions break the larger molecules forming the solid kerogen into smaller molecules of oil and gas. The thermal conversion process is referred to as pyrolysis or retorting.

[0009] Attempts have been made for many years to extract oil from oil shale formations. Near-surface oil shales have been mined and retorted at the surface for over a century. In 1862, James Young began processing Scottish oil shales. The industry lasted for about 100 years. Commercial oil shale retorting through surface mining has been conducted in other countries as well. Such countries include Australia, Brazil, China, Estonia, France, Russia, South Africa, Spain, and Sweden. However, the practice has been mostly discontinued in recent years because it has proven to be uneconomical or because of environmental constraints on spent shale disposal. (See T. F. Yen, and G. V. Chilingarian, “*Oil Shale*,” Amsterdam, Elsevier, p. 292, the entire disclosure of which is incorporated herein by reference.) Further, surface retorting requires mining of the oil shale, which limits that particular application to very shallow formations.

[0010] In the United States, the existence of oil shale deposits in northwestern Colorado has been known since the early 1900's. While research projects have been conducted in this area from time to time, no serious commercial development has been undertaken. Most research on oil shale production has been carried out in the latter half of the 1900's. The majority of this research was on shale oil geology, geochemistry, and retorting in surface facilities.

[0011] In 1947, U.S. Pat. No. 2,732,195 issued to Ljungstrom. That patent, entitled “Method of Treating Oil Shale and Recovery of Oil and Other Mineral Products Therefrom,” proposed the application of heat at high temperatures to the oil shale formation in situ. The purpose of such in situ heating was to distill hydrocarbons and produce them to the surface. The ’195 Ljungstrom patent is incorporated herein by reference.

[0012] Ljungstrom coined the phrase “heat supply channels” to describe bore holes drilled into the formation. The bore holes received an electrical heat conductor which transferred heat to the surrounding oil shale. Thus, the heat supply channels served as early heat injection wells. The electrical heating elements in the heat injection wells were placed within sand or cement or other heat-conductive material to permit the heat injection wells to transmit heat into the surrounding oil shale while preventing the inflow of fluid. According to Ljungstrom, the “aggregate” was heated to between 500° and 1,000° C. in some applications.

[0013] Along with the heat injection wells, fluid producing wells were also completed in near proximity to the heat injection wells. As kerogen was pyrolyzed upon heat conduction into the rock matrix, the resulting oil and gas would be recovered through the adjacent producing wells.

[0014] Ljungstrom applied his approach of thermal conduction from heated wellbores through the Swedish Shale Oil Company. A full scale plant was developed that operated from 1944 into the 1950's. (See G. Salamonsson, “The Ljungstrom In Situ Method for Shale-Oil Recovery,” 2[nd] Oil Shale and Cannel Coal Conference, v. 2, Glasgow, Scotland, Institute of Petroleum, London, p. 260-280 (1951), the entire disclosure of which is incorporated herein by reference.)

[0015] Additional in situ methods have been proposed. These methods generally involve the injection of heat and/or solvent into a subsurface oil shale formation. Heat may be in the form of heated methane (see U.S. Pat. No. 3,241,611 to J. L. Dougan), flue gas, or superheated steam (see U.S. Pat. No.

3,400,762 to D. W. Peacock). Heat may also be in the form of electric resistive heating, dielectric heating, radio frequency (RF) heating (U.S. Pat. No. 4,140,180, assigned to the ITT Research Institute in Chicago, Ill.) or oxidant injection to support in situ combustion. In some instances, artificial permeability has been created in the matrix to aid the movement of pyrolyzed fluids. Permeability generation methods include mining, rubblization, hydraulic fracturing (see U.S. Pat. No. 3,468,376 to M. L. Slusser and U.S. Pat. No. 3,513,914 to J. V. Vogel), explosive fracturing (see U.S. Pat. No. 1,422,204 to W. W. Hoover, et al.), heat fracturing (see U.S. Pat. No. 3,284,281 to R. W. Thomas), and steam fracturing (see U.S. Pat. No. 2,952,450 to H. Purre).

[0016] In 1989, U.S. Pat. No. 4,886,118 issued to Shell Oil Company, the entire disclosure of which is incorporated herein by reference. That patent, entitled "Conductively Heating a Subterranean Oil Shale to Create Permeability and Subsequently Produce Oil," declared that "[c]ontrary to the implications of . . . prior teachings and beliefs . . . the presently described conductive heating process is economically feasible for use even in a substantially impermeable subterranean oil shale." (col. 6, ln. 50-54). Despite this declaration, it is noted that few, if any, commercial in situ shale oil operations have occurred other than Ljungstrom's enterprise. The '118 patent proposed controlling the rate of heat conduction within the rock surrounding each heat injection well to provide a uniform heat front.

[0017] As indicated above, resistive heating techniques for a subsurface formation have been considered. F. S. Chute and F. E. Vermeulen, Present and Potential Applications of Electromagnetic Heating in the In Situ Recovery of Oil, AOSTRA J. Res., v. 4, p. 19-33 (1988) describes a heavy-oil pilot test where "electric preheat" was used to flow electric current between two wells to lower viscosity and create communication channels between wells for follow-up with a steam flood. It has been disclosed to run alternating current or radio frequency electrical energy between stacked conductive fractures or electrodes in the same well in order to heat a subterranean formation. See U.S. Pat. No. 3,149,672 titled "Method and Apparatus for Electrical Heating of Oil-Bearing Formations;" U.S. Pat. No. 3,620,300 titled "Method and Apparatus for Electrically Heating a Subsurface Formation;" U.S. Pat. No. 4,401,162 titled "In Situ Oil Shale Process;" and U.S. Pat. No. 4,705,108 titled "Method for In Situ Heating of Hydrocarbonaceous Formations." U.S. Pat. No. 3,642,066 titled "Electrical Method and Apparatus for the Recovery of Oil," provides a description of resistive heating within a subterranean formation by running alternating current between different wells. Others have described methods to create an effective electrode in a wellbore. See U.S. Pat. No. 4,567,945 titled "Electrode Well Method and Apparatus;" and U.S. Pat. No. 5,620,049 titled "Method for Increasing the Production of Petroleum From a Subterranean Formation Penetrated by a Wellbore." U.S. Pat. No. 3,137,347 titled "In Situ Electrolinking of Oil Shale," describes a method by which electric current is flowed through a fracture connecting two wells to get electric flow started in the bulk of the surrounding formation. Heating of the formation occurs primarily due to the bulk electrical resistance of the formation.

[0018] Additional history behind oil shale retorting and shale oil recovery can be found in co-owned U.S. Pat. No. 7,331,385 entitled "Methods of Treating a Subterranean Formation to Convert Organic Matter into Producible Hydrocarbons." The Background and technical disclosure of this patent is incorporated herein by reference.

[0019] A need exists for improved processes for the production of shale oil. In addition, a need exists for improved methods for heating a subsurface formation. Still further, a need exists for methods that facilitate an expeditious and effective subsurface heater well arrangement using an electrically conductive granular material placed within an organic-rich rock formation.

SUMMARY

[0020] In one embodiment, a method for heating a subsurface formation using electrical resistance heating is provided. In one aspect, the method includes providing two or more wellbores that penetrate an interval of solid organic-rich rock within the subsurface formation. Preferably, the organic-rich rock comprises oil shale.

[0021] At least one fracture is established in the organic-rich rock from at least one of the two or more wellbores. Preferably, the at least one fracture is formed hydraulically. The method also includes placing electrically conductive material in the at least one fracture. In this way electrical communication is provided between the two or more wellbores. The electrically conductive material comprises first portions placed in contact with each of the two or more wellbores, and a second portion intermediate the first portions and around the two or more wellbores. The first portions have a first bulk resistivity while the second portion has a second bulk resistivity.

[0022] The method also includes passing electric current through the fracture such that heat is generated by electrical resistivity within the electrically conductive material sufficient to pyrolyze at least a portion of the organic-rich rock into hydrocarbon fluids. The heat generated within the first portions of the electrically conductive material is less than the heat generated within the second portion of the electrically conductive material.

[0023] In one embodiment, each of the two or more wellbores is completed substantially vertically, and the at least one fracture is substantially horizontal. In another embodiment, each of the two or more wellbores is completed substantially horizontally, and the at least one fracture is substantially vertical.

[0024] The electrically conductive material preferably comprises a proppant material. In one aspect, the first portions of the electrically conductive material comprise granular metal, metal coated particles, coke, graphite, or combinations thereof. In another aspect, the second portion of the electrically conductive material comprises granular metal, metal coated particles, coke, graphite, or combinations thereof.

[0025] As noted, the resistivity of the first portions is different than in the second portion. In one aspect, the resistivity of the material comprising the second portion of the electrically conductive material is about 10 to 100 times greater than the resistivity of the material comprising the first portions of the electrically conductive material. In one example, and by way of example only, the resistivity of the first portions of the electrically conductive material may be about 0.005 Ohm-meters. Alternatively, the resistivities of the first portions may be about 0.00005 Ohm-meters, or even as low as 0.00001 Ohm-Meters.

[0026] In another aspect, the first portions of the electrically conductive material are substantially non-conductive, and the second portion of the electrically conductive material contacts at least a portion of each of the two or more wellbores. Examples of non-conductive materials include silica, quartz, cement chips, sandstone, or combinations thereof. In one example, and by way of example only, the resistivity of the first portions of the electrically conductive material approaches infinity.

[0027] In one embodiment, the method also includes the step of continuing to pass electrical current through the first and second conductive portions of electrically conductive material. In this way pyrolysis of oil shale into hydrocarbon fluids occurs. The hydrocarbon fluids may then be produced from the subsurface formation to a surface processing facility.

[0028] Another method for heating a subsurface formation using electrical resistance heating is provided herein. Preferably, the subsurface formation is an organic-rich rock formation. Preferably, the subsurface formation contains heavy hydrocarbons. More preferably, the subsurface formation is an oil shale formation.

[0029] The method includes creating at least one passage in the subsurface formation between a first wellbore located at least partially within the subsurface formation and a second wellbore also located at least partially within the subsurface formation. An electrically conductive material is placed into the at least one passage to form an electrical connection. The electrical connection provides electrical communication between the first wellbore and the second wellbore. The electrically conductive material may be a granular material.

[0030] The method also includes providing a first electrically conductive member in the first wellbore so that the first electrically conductive member is in electrical communication with the electrical connection, and providing a second electrically conductive member in the second wellbore so that the second electrically conductive member is also in electrical communication with the electrical connection. In this way, an electrically conductive flow path comprised at least of the first electrically conductive member, the electrical connection and the second electrically conductive member is formed.

[0031] The method also includes establishing an electrical current through the electrically conductive flow path. This generates heat within the electrically conductive flow path due to electrical resistive heating. At least a portion of the generated heat thermally conducts into the subsurface formation. In accordance with this method, the generated heat is comprised of first heat generated in proximity to the first electrically conductive member and the second electrically conductive member, and second heat generated from the electrically conductive material intermediate the first electrically conductive member and the second electrically conductive member. The first heat is less than the second heat. Preferably, the generated heat causes pyrolysis of solid hydrocarbons within at least a portion of the subsurface formation.

[0032] In one embodiment, the electrically conductive material comprises (i) first portions in immediate proximity to the first electrically conductive member and the second electrically conductive member, respectively, and (ii) a second portion intermediate the first portions around the first and second electrically conductive members. A resistivity of the first portion is different than a resistivity of the second portion. In one aspect, the first portions of the electrically conductive material have a sufficiently low electrical resistivity so as to provide electrical conduction without substantial heat generation.

[0033] For example, the first portions of the electrically conductive granular material may include less than or equal to 50 percent by dry weight of cement and 50 percent or more by dry weight of graphite. The first portions of the electrically conductive granular material may include between 50 to 75 percent of granular metal, metal coated particles, coke, graphite, or combinations thereof.

[0034] In one general aspect, a method for heating a subsurface formation using electrical resistance heating includes providing two or more wellbores that penetrate an interval of solid organic-rich rock within the subsurface formation; establishing at least one fracture in the organic-rich rock from at least one of the two or more wellbores; and providing electrically conductive material in the at least one fracture so as to provide electrical communication between the two or more wellbores. The electrically conductive material includes (i) first portions placed in contact with each of the two or more wellbores and having a first bulk resistivity, and (ii) a second electrically conductive portion intermediate the two or more wellbores and having a second bulk resistivity. Electric current is passed through the at least one fracture such that resistive heat is generated within the electrically conductive material sufficient to pyrolyze at least a portion of the organic-rich rock into hydrocarbon fluids, wherein the generated heat is lower within the first portions of the electrically conductive material than in the second portion of the electrically conductive material.

[0035] Implementations of this aspect may include one or more of the following features. For example, the organic-rich rock may include oil shale. Each of the two or more wellbores may be completed substantially vertically and/or horizontally. The at least one fracture may be substantially horizontal, vertical, or some combination thereof. The electrically conductive material may include a granular material that serves as a proppant. The first portions of the electrically conductive material may include granular metal, metal coated particles, coke, graphite, and/or any combination thereof. The second portion of the electrically conductive material may include granular metal, metal coated particles, coke, graphite, and/or any combination thereof. The resistivity of the material comprising the second portion of the electrically conductive material may be about 10 to 100 times greater than the resistivity of the material comprising the first portions of the electrically conductive material. The first portions of the electrically conductive material may be substantially non-conductive. The second portion of the electrically conductive material may contact at least a portion of each of the two or more wellbores. The first portions of the electrically conductive material may include silica, quartz, cement chips, sandstone, and/or any combination thereof. The resistivity of the first portions of the electrically conductive material may be about 0.005 Ohm-Meters. The resistivity of the first portions of the electrically conductive material may be between about 0.00001 Ohm-Meters and 0.00005 Ohm-Meters. The resistivity of the first portions of the electrically conductive material may approach infinity. The at least one fracture may be formed hydraulically. Electrical current may be continually or intermittently passed through the first and second portions of electrically conductive material so as to cause pyrolysis of oil shale into hydrocarbon fluids. Hydrocarbon fluids may be produced from the subsurface formation to a surface processing facility, e.g., with one or more production wells.

[0036] In another general aspect, a method for heating a subsurface formation using electrical resistance heating includes creating at least one passage in the subsurface formation between a first wellbore located at least partially within the subsurface formation and a second wellbore also located at least partially within the subsurface formation. An electrically conductive material is provided into the at least one passage to form an electrical connection, the electrical connection providing electrical communication between the first wellbore and the second wellbore. A first electrically conductive member is provided in the first wellbore so that the first electrically conductive member is in electrical communication with the electrical connection. A second electrically conductive member is provided in the second wellbore, so that the second electrically conductive member is in electrical communication with the electrical connection, thereby forming an electrically conductive flow path comprised at least of the first electrically conductive member, the electrical connection and the second electrically conductive member. An electrical current may be established through the electrically conductive flow path, thereby generating heat within the electrically conductive flow path due to electrical resistive heating, with at least a portion of the generated heat thermally conducting into the subsurface formation, and wherein the generated heat is comprised of first heat generated in proximity to the first electrically conductive member and the second electrically conductive member, and second heat generated from the electrically conductive granular material intermediate the first electrically conductive member and the second electrically conductive member, with the first heat being less than the second heat.

[0037] Implementations of this aspect may include one or more of the following features. For example, the subsurface formation may be an organic-rich rock formation. The subsurface formation may contain heavy hydrocarbons. The subsurface formation may be an oil shale formation. The electrically conductive material may include a granular material. The electrical connection may include a granular electrical connection. The generated heat causes pyrolysis of solid hydrocarbons within at least a portion of the subsurface formation. The electrically conductive granular material may include (i) first portions in immediate proximity to the first electrically conductive member and the second electrically conductive member, respectively, and (ii) a second portion intermediate the first portions around the first and second electrically conductive members. The resistivity of the first portions may be different than a resistivity of the second portion. The first portions of the electrically conductive granular material may have a sufficiently low electrical resistivity so as to provide electrical conduction without substantial heat generation. The first portions of the electrically conductive granular material may include granular metal, metal coated particles, coke, graphite, and/or any combination thereof. The second portion of the electrically conductive granular material may include granular metal, metal coated particles, coke, graphite, and/or any combination thereof. The resistivity of the material comprising the second portion of the electrically conductive granular material may be about 10 to 100 times greater than the resistivity of the material comprising the first portions of the electrically conductive granular material. The first portions of the electrically conductive granular material may include less than or equal to 50 percent by dry weight of cement and 50 percent or more by dry weight of graphite. The first portions of the electrically conductive granular material may include between 50 to 75 percent of granular metal, metal coated particles, coke, graphite, and/or any combination thereof. The first portions of the electrically conductive granular material may be substantially non-conductive; and the second portion of the electrically conductive granular material contacts at least a portion of each of the first and second electrically conductive members. The first portions of the electrically conductive granular material may include silica, quartz, cement chips, sandstone, and/or any combination thereof. The resistivity of the first portions of the electrically conductive granular material may be about 0.005 Ohm-meters. The resistivity of the first portions of the electrically conductive material may approach infinity. The first wellbore and the second wellbore may each be completed substantially vertically; and the passage in the subsurface formation may include a substantially vertically fracture. The first wellbore and the second wellbore may each be completed substantially horizontally; and the at least one passage in the subsurface formation may include a first substantially vertical fracture. A third electrically conductive member may be provided in a third wellbore, such that the third electrically conductive member is also in electrical communication with the electrical connection and is part of the electrically conductive flow path. The third wellbore may be completed substantially horizontally. The at least one passage in the subsurface formation may include a second substantially vertical fracture. The second wellbore may intersect both the first fracture and the second fracture. The material comprising at least a portion of the first electrically conductive member, the second electrically conductive member, or both may have an electrical resistivity of less than 0.0005 Ohm-meters. An electrical current may be continually or intermittently passed through the electrical connection until the subsurface formation immediately adjacent the electrically conductive flow path reaches a selected temperature; and reducing an amount of current through the electrical connection.

[0038] In another general aspect, a system for in situ heating of a subsurface formation using electrical resistance heating includes a plurality of wellbores that penetrate an interval of solid organic-rich rock within the subsurface formation. At least one fracture in the organic-rich rock is established from at least one of the wellbores, wherein the at least one fracture includes electrically conductive material to provide electrical communication between at least two of the wellbores. The electrically conductive material may include (i) first portions placed in contact with at least two wellbores and having a first bulk resistivity, and (ii) a second electrically conductive portion intermediate the at least two wellbores and having a second bulk resistivity. At least one electrical conductor is operatively connected to the first portions of the electrically conductive material in each of the at least two wellbores, the at least one electrical conductor being configured to pass electric current through the at least one fracture such that resistive heat is generated within the electrically conductive material sufficient to pyrolyze at least a portion of the organic-rich rock into hydrocarbon fluids. The generated heat may be lower within the first portions of the electrically conductive material than in the second portion of the electrically conductive material.

[0039] Implementations of this aspect may include one or more of the following features. For example, each of the two or more wellbores may be completed substantially vertically, horizontally, or some combination thereof. The at least one fracture may be substantially horizontal, vertical, or some combination thereof. The electrically conductive material may include a granular material that serves as a proppant. The first portions of the electrically conductive material may include granular metal, metal coated particles, coke, graphite, and/or any combination thereof. The second portion of the electrically conductive material may include granular metal, metal coated particles, coke, graphite, and/or any combination thereof. The resistivity of the material comprising the second portion of the electrically conductive material may be about 10 to 100 times greater than the resistivity of the material comprising the first portions of the electrically conductive material. The first portions of the electrically conductive material may be substantially non-conductive. The second portion of the electrically conductive material may contact at least a portion of each of the two or more wellbores. The first portions of the electrically conductive material may include silica, quartz, cement chips, sandstone, and/or any combination thereof. The resistivity of the first portions of the electrically conductive material may be about 0.005 Ohm-Meters. The resistivity of the first portions of the electrically conductive material may be between about 0.00001 Ohm-Meters and 0.00005 Ohm-Meters. The resistivity of the first portions of the electrically conductive material may approach infinity. The at least one fracture may be formed hydraulically. The system may include one or more production wells for producing hydrocarbon fluids from the subsurface formation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0040] So that the present invention can be better understood, certain drawings, charts, graphs and flow charts are appended hereto. It is to be noted, however, that the drawings illustrate only selected embodiments of the inventions and are therefore not to be considered limiting of scope, for the inventions may admit to other equally effective embodiments and applications.

[0041] FIG. **1** is a cross-sectional isometric view of an illustrative subsurface area. The subsurface area includes an organic-rich rock matrix that defines a subsurface formation.

[0042] FIG. **2** is a flow chart demonstrating a general method of in situ thermal recovery of oil and gas from an organic-rich rock formation, in one embodiment.

[0043] FIG. **3** is a cross-sectional side view of an illustrative oil shale formation that is within or connected to groundwater aquifers, and a formation leaching operation.

[0044] FIG. **4** is a plan view of an illustrative heater well pattern. Two layers of heater wells are shown around respective production wells.

[0045] FIG. **5** is a bar chart comparing one ton of Green River oil shale before and after a simulated in situ, retorting process.

[0046] FIG. **6** is a process flow diagram of exemplary surface processing facilities for a subsurface formation development.

[0047] FIG. **7** is a perspective view of a hydrocarbon development area. A subsurface formation is being heated via resistive heating. A mass of conductive granular material has been injected into the formation between two adjacent wellbores.

[0048] FIG. **8**A is a perspective view of another hydrocarbon development area. A subsurface formation is once again being heated via resistive heating. A mass of conductive granular material has been injected into the formation from a plurality of horizontally completed wellbores. Corresponding wellbores are completed horizontally through the individual masses of conductive granular material.

[0049] FIG. **8**B is yet another perspective view of a hydrocarbon development area. A subsurface formation is once again being heated via resistive heating. A mass of conductive granular material has been injected into the formation from a pair of horizontally completed wellbores. A third wellbore is completed horizontally through the masses of conductive granular material.

[0050] FIG. **9** is a perspective view of a core sample that has been opened along its longitudinal axis. Steel shot has been placed within a "tray" formed internal to the core sample.

[0051] FIG. **10** shows the core sample of FIG. **9** having been closed and clamped for testing. A current is run through the length of the core sample to create resistive heating.

[0052] FIG. **11** provides a series of charts wherein power, temperature and resistance are measured as a function of time during the heating of the core sample of FIG. **9**.

[0053] FIG. **12** demonstrates a flow of current through a geologic formation that has been fractured. Arrows demonstrate current increments in the x and y directions for partial derivative equations.

[0054] FIG. **13** is a thickness-conductivity map showing a plan view of a simulated fracture. Two steel plates are positioned within surrounding conductive granular proppant within the fracture. The map is gray-scaled to show the product value of conductivity multiplied by the thickness of the conductive granular proppant across the fracture.

[0055] FIG. **14** is another view of the thickness-conductivity map of FIG. **13**. The map is gray-scaled in finer increments of conductivity multiplied by thickness to distinguish variations in proppant thickness.

[0056] FIG. **15** is a representation of electric current moving into and out of the fracture plane of FIG. **13**. This representation is an electric current source map.

[0057] FIG. **16** shows a voltage distribution within the fracture of FIG. **13**.

[0058] FIG. **17** shows a heating distribution within the fracture of FIG. **13**.

[0059] FIG. **18** is a thickness-conductivity map showing a plan view of a simulated fracture plane. Two steel plates are again positioned within surrounding conductive granular proppants within the fracture plane. The map is gray-scaled to show the product value of conductivity multiplied by the thickness of the conductive granular proppants across the fracture.

[0060] FIG. **19** is another view of the thickness-conductivity map of FIG. **18**. The map is gray-scaled in finer increments of conductivity multiplied by thickness to distinguish product values between the calcined coke, around the steel plates and a higher conductivity proppant, or "connector."

[0061] FIG. **20** is another view of the thickness-conductivity map of FIG. **18**. The map is gray-scaled in still further finer increments of conductivity times thickness to distinguish variations in conductivity between the calcined coke around the steel plates and the higher conductivity proppant.

[0062] FIG. **21** is a representation of electric current moving into and out of the fracture plane of FIG. **18**. This representation is an electric current source map.

[0063] FIG. **22** shows a voltage distribution within the fracture plane of FIG. **18**.

[0064] FIG. **23** shows a heating distribution within the fracture plane of FIG. **18**.

[0065] FIG. **24** is a thickness-conductivity map showing a plan view of a simulated fracture plane. Two steel plates are again positioned within surrounding conductive granular proppants within the fracture plane. The map is gray-scaled to show the product value of conductivity multiplied by thickness for the conductive granular proppants across the fracture.

[0066] FIG. 25 is another view of the thickness-conductivity map of FIG. 24. The map is gray-scaled in finer increments of conductivity multiplied by thickness to distinguish between calcined coke, or "connector," around the steel plates and a higher conductivity proppant.

[0067] FIG. 26 is a representation of electric current moving into and out of the fracture plane of FIG. 24. This representation is an electric current source map.

[0068] FIG. 27 shows a voltage distribution within the fracture plane of FIG. 24.

[0069] FIG. 28 shows a heating distribution within the fracture plane of FIG. 24.

DETAILED DESCRIPTION

Definitions

[0070] As used herein, the term "hydrocarbon(s)" refers to organic material with molecular structures containing carbon bonded to hydrogen. Hydrocarbons may also include other elements such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur.

[0071] As used herein, the term "hydrocarbon fluids" refers to a hydrocarbon or mixtures of hydrocarbons that are gases or liquids. For example, hydrocarbon fluids may include a hydrocarbon or mixtures of hydrocarbons that are gases or liquids at formation conditions, at processing conditions or at ambient conditions (15° C. and 1 atm pressure). Hydrocarbon fluids may include, for example, oil, natural gas, coal bed methane, shale oil, pyrolysis oil, pyrolysis gas, a pyrolysis product of coal, and other hydrocarbons that are in a gaseous or liquid state.

[0072] As used herein, the terms "produced fluids" and "production fluids" refer to liquids and/or gases removed from a subsurface formation, including, for example, an organic-rich rock formation. Production fluids may include, but are not limited to, pyrolyzed shale oil, synthesis gas, a pyrolysis product of coal, carbon dioxide, hydrogen sulfide and water (including steam). Produced fluids may include both hydrocarbon fluids and non-hydrocarbon fluids.

[0073] As used herein, the term "condensable hydrocarbons" means those hydrocarbons that condense at 25° C. and one atmosphere absolute pressure. Condensable hydrocarbons may include a mixture of hydrocarbons having carbon numbers greater than 4.

[0074] As used herein, the term "non-condensable hydrocarbons" means those hydrocarbons that do not condense at 25° C. and one atmosphere absolute pressure. Non-condensable hydrocarbons may include hydrocarbons having carbon numbers less than 5.

[0075] As used herein, the term "heavy hydrocarbons" refers to hydrocarbon fluids that are highly viscous at ambient conditions (15° C. and 1 atm pressure). Heavy hydrocarbons may include highly viscous hydrocarbon fluids such as heavy oil, tar, and/or asphalt. Heavy hydrocarbons may include carbon and hydrogen, as well as smaller concentrations of sulfur, oxygen, and nitrogen. Additional elements may also be present in heavy hydrocarbons in trace amounts. Heavy hydrocarbons may be classified by API gravity. Heavy hydrocarbons generally have an API gravity below about 20 degrees. Heavy oil, for example, generally has an API gravity of about 10 to 20 degrees, whereas tar generally has an API gravity below about 10 degrees. The viscosity of heavy hydrocarbons is generally greater than about 100 centipoise at 15° C.

[0076] 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.

[0077] As used herein, the term "formation hydrocarbons" refers to both heavy hydrocarbons and solid hydrocarbons that are contained in an organic-rich rock formation. Formation hydrocarbons may be, but are not limited to, kerogen, oil shale, coal, bitumen, tar, natural mineral waxes, and asphaltites.

[0078] As used herein, the term "tar" refers to a viscous hydrocarbon that generally has a viscosity greater than about 10,000 centipoise at 15° C. The specific gravity of tar generally is greater than 1.000. Tar may have an API gravity less than 10 degrees. "Tar sands" refers to a formation that has tar in it.

[0079] As used herein, the term "kerogen" refers to a solid, insoluble hydrocarbon that principally contains carbon, hydrogen, nitrogen, oxygen, and sulfur. Oil shale contains kerogen.

[0080] As used herein, the term "bitumen" refers to a non-crystalline solid or viscous hydrocarbon material that is substantially soluble in carbon disulfide.

[0081] As used herein, the term "oil" refers to a hydrocarbon fluid containing a mixture of condensable hydrocarbons.

[0082] As used herein, the term "subsurface" refers to geologic strata occurring below the earth's surface.

[0083] As used herein, the term "hydrocarbon-rich formation" refers to any formation that contains more than trace amounts of hydrocarbons. For example, a hydrocarbon-rich formation may include portions that contain hydrocarbons at a level of greater than 5 volume percent. The hydrocarbons located in a hydrocarbon-rich formation may include, for example, oil, natural gas, heavy hydrocarbons, and solid hydrocarbons.

[0084] 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.

[0085] As used herein, the term "formation" refers to any finite subsurface region. The formation may contain one or more hydrocarbon-containing layers, one or more non-hydrocarbon containing layers, an overburden, and/or an underburden of any subsurface geologic formation. An "overburden" is geological material above the formation of interest, while an "underburden" is geological material below the formation of interest. An overburden or underburden may include one or more different types of substantially impermeable materials. For example, overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate (i.e., an impermeable carbonate without hydrocarbons). An overburden and/or an underburden may include a hydrocarbon-containing layer that is relatively impermeable. In some cases, the overburden and/or underburden may be permeable.

[0086] 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, and tar sands formations.

[0087] 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.

[0088] As used herein, the term "water-soluble minerals" refers to minerals that are soluble in water. Water-soluble minerals include, for example, nahcolite (sodium bicarbonate), soda ash (sodium carbonate), dawsonite ($NaAl(CO_3)(OH)_2$), or combinations thereof. Substantial solubility may require heated water and/or a non-neutral pH solution.

[0089] As used herein, the term "formation water-soluble minerals" refers to water-soluble minerals that are found naturally in a formation.

[0090] As used herein, the term "subsidence" refers to a downward movement of a surface relative to an initial elevation of the surface.

[0091] As used herein, the term "thickness" of a layer refers to the distance between the upper and lower boundaries of a cross section of a layer, wherein the distance is measured normal to the average tilt of the cross section.

[0092] As used herein, the term "thermal fracture" refers to fractures created in a formation caused directly or indirectly by expansion or contraction of a portion of the formation and/or fluids within the formation, which in turn is caused by increasing/decreasing the temperature of the formation and/or fluids within the formation, and/or by increasing/decreasing a pressure of fluids within the formation due to heating. Thermal fractures may propagate into or form in neighboring regions significantly cooler than the heated zone.

[0093] As used herein, the term "hydraulic fracture" refers to a fracture at least partially propagated into a formation, wherein the fracture is created through injection of pressurized fluids into the formation. While the term "hydraulic fracture" is used, the inventions herein are not limited to use in hydraulic fractures. The invention is suitable for use in any fracture created in any manner considered to be suitable by one skilled in the art. The fracture may be artificially held open by injection of a proppant material. Hydraulic fractures may be substantially horizontal in orientation, substantially vertical in orientation, or oriented along any other plane.

[0094] As used herein, the term "wellbore" refers to a hole in the subsurface made by drilling or insertion of a conduit into the subsurface. A wellbore may have a substantially circular cross section, or other cross-sectional shapes (e.g., circles, ovals, squares, rectangles, triangles, slits, or other regular or irregular shapes). As used herein, the term "well", when referring to an opening in the formation, may be used interchangeably with the term "wellbore."

[0095] The inventions are described herein in connection with certain specific embodiments. However, to the extent that the following detailed description is specific to a particular embodiment or a particular use, such is intended to be illustrative only and is not to be construed as limiting the scope of the invention.

[0096] As discussed herein, some embodiments of the invention include or have application related to an in situ method of recovering natural resources. The natural resources may be recovered from an organic-rich rock formation including, for example, an oil shale formation. The organic-rich rock formation may include formation hydrocarbons including, for example, kerogen, coal, and heavy hydrocarbons. In some embodiments of the invention the natural resources may include hydrocarbon fluids including, for example, products of the pyrolysis of formation hydrocarbons such as shale oil. In some embodiments of the invention the natural resources may also include water-soluble minerals including, for example, nahcolite (sodium bicarbonate, or $2NaHCO_3$), soda ash (sodium carbonate, or Na_2CO_3) and dawsonite ($NaAl(CO_3)(OH)_2$).

[0097] FIG. **1** presents a perspective view of an illustrative oil shale development area **10**. A surface **12** of the development area **10** is indicated. Below the surface is an organic-rich rock formation **16**. The illustrative subsurface formation **16** contains formation hydrocarbons (such as, for example, kerogen) and possibly valuable water-soluble minerals (such as, for example, nahcolite). It is understood that the representative formation **16** may be any organic-rich rock formation, including a rock matrix containing coal or tar sands, for example. In addition, the rock matrix making up the formation **16** may be permeable, semi-permeable or essentially non-permeable. The present inventions are particularly advantageous in oil shale development areas initially having very limited or effectively no fluid permeability.

[0098] In order to access formation **16** and recover natural resources therefrom, a plurality of wellbores is formed. Wellbores are shown at **14** in FIG. **1**. The representative wellbores **14** are essentially vertical in orientation relative to the surface **12**. However, it is understood that some or all of the wellbores **14** could deviate into an obtuse or even horizontal orientation. In the arrangement of FIG. **1**, each of the wellbores **14** is completed in the oil shale formation **16**. The completions may be either open or cased hole. The well completions may also include propped or unpropped hydraulic fractures emanating therefrom.

[0099] In the view of FIG. **1**, only seven wellbores **14** are shown. However, it is understood that in an oil shale development project, numerous additional wellbores **14** will most likely be drilled. The wellbores **14** may be located in relatively close proximity, being from 10 feet to up to 300 feet in separation. In some embodiments, a well spacing of 15 to 25 feet is provided. Typically, the wellbores **14** are also completed at shallow depths, being from 200 to 5,000 feet at total depth. In some embodiments the oil shale formation targeted for in situ retorting is at a depth greater than 200 feet below the surface or alternatively 400 feet below the surface. Alternatively, conversion and production occur at depths between 500 and 2,500 feet.

[0100] The wellbores **14** will be selected for certain functions and may be designated as heat injection wells, water injection wells, oil production wells and/or water-soluble mineral solution production wells. In one aspect, the wellbores **14** are dimensioned to serve two, three, or all four of these purposes in designated sequences. Suitable tools and equipment may be sequentially run into and removed from the wellbores **14** to serve the various purposes.

[0101] A fluid processing facility **17** is also shown schematically. The fluid processing facility **17** is equipped to receive fluids produced from the organic-rich rock formation **16** through one or more pipelines or flow lines **18**. The fluid processing facility **17** may include equipment suitable for receiving and separating oil, gas, and water produced from the heated formation. The fluid processing facility **17** may further include equipment for separating out dissolved water-soluble minerals and/or migratory contaminant species, including, for example, dissolved organic contaminants, metal contaminants, or ionic contaminants in the produced water recovered from the organic-rich rock formation **16**. The contaminants may include, for example, aromatic hydrocarbons such as benzene, toluene, xylene, and tri-methylbenzene. The contaminants may also include polyaromatic hydrocarbons such as anthracene, naphthalene, chrysene and pyrene. Metal contaminants may include species containing arsenic, boron, chromium, mercury, selenium, lead, vanadium, nickel, cobalt, molybdenum, or zinc. Ionic contaminant species may include, for example, sulfates, chlorides, fluorides, lithium, potassium, aluminum, ammonia, and nitrates.

[0102] In order to recover oil, gas, and sodium (or other) water-soluble minerals, a series of steps may be undertaken. FIG. **2** presents a flow chart demonstrating a method of in situ thermal recovery of oil and gas from an organic-rich rock formation **100**, in one embodiment. It is understood that the order of some of the steps from FIG. **2** may be changed, and that the sequence of steps is merely for illustration.

[0103] First, the oil shale (or other organic-rich rock) formation **16** is identified within the development area **10**. This step is shown in box **110**. Optionally, the oil shale formation may contain nahcolite or other sodium minerals. The targeted development area within the oil shale formation may be identified by measuring or modeling the depth, thickness and organic richness of the oil shale as well as evaluating the position of the organic-rich rock formation relative to other rock types, structural features (e.g. faults, anticlines or synclines), or hydrogeological units (i.e. aquifers). This is accomplished by creating and interpreting maps and/or models of depth, thickness, organic richness and other data from available tests and sources. This may involve performing geological surface surveys, studying outcrops, performing seismic surveys, and/or drilling boreholes to obtain core samples from subsurface rock. Rock samples may be analyzed to assess kerogen content and hydrocarbon fluid generating capability.

[0104] The kerogen content of the organic-rich rock formation may be ascertained from outcrop or core samples using a variety of data. Such data may include organic carbon content, hydrogen index, and modified Fischer assay analyses. Subsurface permeability may also be assessed via rock samples, outcrops, or studies of ground water flow. Furthermore the connectivity of the development area to ground water sources may be assessed.

[0105] Next, a plurality of wellbores **14** is formed across the targeted development area **10**. This step is shown schematically in box **115**. The purposes of the wellbores **14** are set forth above and need not be repeated. However, it is noted that for purposes of the wellbore formation step of box **115**, only a portion of the wells need be completed initially. For instance, at the beginning of the project heat injection wells are needed, while a majority of the hydrocarbon production wells are not yet needed. Production wells may be brought in once conversion begins, such as after 4 to 12 months of heating.

[0106] It is understood that petroleum engineers will develop a strategy for the best depth and arrangement for the wellbores **14**, depending upon anticipated reservoir characteristics, economic constraints, and work scheduling constraints. In addition, engineering staff will determine what wellbores **14** shall be used for initial formation **16** heating. This selection step is represented by box **120**.

[0107] Concerning heat injection wells, there are various methods for applying heat to the organic-rich rock formation **16**. The present methods are not limited to the heating technique employed unless specifically so stated in the claims. The heating step is represented generally by box **130**. Preferably, for in situ processes the heating of a production zone takes place over a period of months, or even four or more years.

[0108] The formation **16** is heated to a temperature sufficient to pyrolyze at least a portion of the oil shale in order to convert the kerogen to hydrocarbon fluids. The bulk of the target zone of the formation may be heated to between 270° C. to 800° C. Alternatively, the targeted volume of the organic-rich formation is heated to at least 350° C. to create production fluids. The conversion step is represented in FIG. **2** by box **135**. The resulting liquids and hydrocarbon gases may be refined into products which resemble common commercial petroleum products. Such liquid products include transportation fuels such as diesel, jet fuel and naphtha. Generated gases include light alkanes, light alkenes, H_2, CO_2, CO, and NH_3.

[0109] Conversion of the oil shale will create permeability in the oil shale section in rocks that were originally impermeable. Preferably, the heating and conversion processes of boxes **130** and **135**, occur over a lengthy period of time. In one aspect, the heating period is from three months to four or more years. Also as an optional part of box **135**, the formation **16** may be heated to a temperature sufficient to convert at least a portion of nahcolite, if present, to soda ash. Heat applied to mature the oil shale and recover oil and gas will also convert nahcolite to sodium carbonate (soda ash), a related sodium mineral. The process of converting nahcolite (sodium bicarbonate) to soda ash (sodium carbonate) is described herein.

[0110] In connection with the heating step **130**, the rock formation **16** may optionally be fractured to aid heat transfer or later hydrocarbon fluid production. The optional fracturing step is shown in box **125**. Fracturing may be accomplished by creating thermal fractures within the formation through application of heat. By heating the organic-rich rock and transforming the kerogen to oil and gas, the permeability of portions of the formation are increased via thermal fracture formation and subsequent production of a portion of the hydrocarbon fluids generated from the kerogen. Alternatively, a process known as hydraulic fracturing may be used. Hydraulic fracturing is a process known in the art of oil and gas recovery where a fracture fluid is pressurized within the wellbore above the fracture pressure of the formation, thus developing fracture planes within the formation to relieve the pressure generated within the wellbore. Hydraulic fractures may be used to create additional permeability in portions of the formation and/or be used to provide a planar source for heating.

[0111] International patent publication WO 2005/010320 entitled "Methods of Treating a Subterranean Formation to Convert Organic Matter into Producible Hydrocarbons" describes one use of hydraulic fracturing, and is incorporated herein by reference in its entirety. This international patent publication teaches the use of electrically conductive fractures to heat oil shale. A heating element is constructed by forming wellbores and then hydraulically fracturing the oil shale formation around the wellbores. The fractures are filled with an electrically conductive material which forms the heating element. Calcined petroleum coke is an exemplary suitable conductant material. Preferably, the fractures are created in a vertical orientation extending from horizontal wellbores. Electricity may be conducted through the conductive fractures from the heel to the toe of each well. The electrical circuit may be completed by an additional horizontal well that intersects one or more of the vertical fractures near the toe to supply the opposite electrical polarity. The WO 2005/010320 process creates an "in situ toaster" that artificially matures oil shale through the application of electric heat. Thermal conduction heats the oil shale to conversion temperatures in excess of 300° C., causing artificial maturation.

[0112] It is noted that U.S. Pat. No. 3,137,347 also describes the use of granular conductive materials to connect subsurface electrodes for the in situ heating of oil shale. The '347 patent envisions the granular material being a primary source of heat until the oil shale undergoes pyrolysis. At that point, the oil shale itself is said to become electrically conductive. Heat generated within the formation and heat conducted into the surrounding formation due to the passing of current through the shale oil material itself is claimed to generate hydrocarbon fluids for production.

[0113] As part of the hydrocarbon fluid production process **100**, certain wells **14** may be designated as oil and gas production wells. This step is depicted by box **140**. Oil and gas production might not be initiated until it is determined that the kerogen has been sufficiently retorted to allow maximum recovery of oil and gas from the formation **16**. In some instances, dedicated production wells are not drilled until after heat injection wells (box **130**) have been in operation for a period of several weeks or months. Thus, box **140** may include the formation of additional wellbores **14**. In other instances, selected heater wells are converted to production wells.

[0114] After certain wellbores **14** have been designated as oil and gas production wells, oil and/or gas is produced from the wellbores **14**. The oil and/or gas production process is shown at box **145**. At this stage (box **145**), any water-soluble minerals, such as nahcolite and converted soda ash may remain substantially trapped in the rock formation **16** as finely disseminated crystals or nodules within the oil shale beds, and are not produced. However, some nahcolite and/or soda ash may be dissolved in the water created during heat conversion (box **135**) within the formation. Thus, production fluids may contain not only hydrocarbon fluids, but also aqueous fluid containing water-soluble minerals. In such case, the production fluids may be separated into a hydrocarbon stream and an aqueous stream at a surface facility. Thereafter the water-soluble minerals and any migratory contaminant species may be recovered from the aqueous stream.

[0115] Box **150** presents an optional next step in the oil and gas recovery method **100**. Here, certain wellbores **14** are designated as water or aqueous fluid injection wells. Aqueous fluids are solutions of water with other species. The water may constitute "brine," and may include dissolved inorganic salts of chloride, sulfates and carbonates of Group I and II elements of The Periodic Table of Elements. Organic salts can also be present in the aqueous fluid. The water may alternatively be fresh water containing other species. The other species may be present to alter the pH. Alternatively, the other species may reflect the availability of brackish water not saturated in the species wished to be leached from the subsurface. Preferably, the water injection wells are selected from some or all of the wellbores used for heat injection or for oil and/or gas production. However, the scope of the step of box **150** may include the drilling of yet additional wellbores **14** for use as dedicated water injection wells. In this respect, it may be desirable to complete water injection wells along a periphery of the development area **10** in order to create a boundary of high pressure.

[0116] Next, optionally water or an aqueous fluid is injected through the water injection wells and into the oil shale formation **16**. This step is shown at box **155**. The water may be in the form of steam or pressurized hot water. Alternatively the injected water may be cool and becomes heated as it contacts the previously heated formation. The injection process may further induce fracturing. This process may create fingered caverns and brecciated zones in the nahcolite-bearing intervals some distance, for example up to 200 feet out, from the water injection wellbores. In one aspect, a gas cap, such as nitrogen, may be maintained at the top of each "cavern" to prevent vertical growth.

[0117] Along with the designation of certain wellbores **14** as water injection wells, the design engineers may also designate certain wellbores **14** as water or water-soluble mineral solution production wells. This step is shown in box **160**. These wells may be the same as wells used to previously produce hydrocarbons or inject heat. These recovery wells may be used to produce an aqueous solution of dissolved water-soluble minerals and other species, including, for example, migratory contaminant species. For example, the solution may be one primarily of dissolved soda ash. This step is shown in box **165**. Alternatively, single wellbores may be used to both inject water and then to recover a sodium mineral solution. Thus, box **165** includes the option of using the same wellbores **14** for both water injection and solution production (Box **165**).

[0118] Temporary control of the migration of the migratory contaminant species, especially during the pyrolysis process, can be obtained via placement of the injection and production wells **14** such that fluid flow out of the heated zone is minimized. Typically, this involves placing injection wells at the periphery of the heated zone so as to cause pressure gradients which prevent flow inside the heated zone from leaving the zone.

[0119] FIG. **3** is a cross-sectional view of an illustrative oil shale formation that is within or connected to ground water aquifers and a formation leaching operation. Four separate oil shale formation zones are depicted (**23**, **24**, **25** and **26**) within the oil shale formation. The water aquifers are below the ground surface **27**, and are categorized as an upper aquifer **20** and a lower aquifer **22**. Intermediate the upper and lower aquifers is an aquitard **21**. It can be seen that certain zones of the formation are both aquifers or aquitards and oil shale zones. A plurality of wells (**28**, **29**, **30** and **31**) is shown traversing vertically downward through the aquifers. One of the wells is serving as a water injection well **31**, while another is serving as a water production well **30**. In this way, water is circulated **32** through at least the lower aquifer **22**.

[0120] FIG. **3** shows diagrammatically water circulating **32** through an oil shale volume **33** that was heated, that resides within or is connected to an aquifer **22**, and from which hydrocarbon fluids were previously recovered. Introduction of water via the water injection well **31** forces water into the previously heated oil shale **33** and water-soluble minerals and migratory contaminants species are swept to the water production well **30**. The water may then be processed in a facility **34** wherein the water-soluble minerals (e.g. nahcolite or soda ash) and the migratory contaminants may be substantially removed from the water stream. Water is then reinjected into the oil shale volume **33** and the formation leaching is repeated. This leaching with water is intended to continue until levels of migratory contaminant species are at environmentally acceptable levels within the previously heated oil shale zone **33**. This may require 1 cycle, 2 cycles, 5 cycles or more cycles of formation leaching, where a single cycle indicates injection and production of approximately one pore volume of water. It is understood that there may be numerous water injection and water production wells in an actual oil shale development. Moreover, the system may include monitoring wells (**28** and **29**) which can be utilized during the oil shale heating phase, the shale oil production phase, the leaching phase, or during any combination of these phases to monitor for migratory contaminant species and/or water-soluble minerals.

[0121] In some fields, formation hydrocarbons, such as oil shale, may exist in more than one subsurface formation. In some instances, the organic-rich rock formations may be separated by rock layers that are hydrocarbon-free or that otherwise have little or no commercial value. Therefore, it may be desirable for the operator of a field under hydrocarbon development to undertake an analysis as to which of the subsurface, organic-rich rock formations to target or in which order they should be developed.

[0122] The organic-rich rock formation may be selected for development based on various factors. One such factor is the thickness of the hydrocarbon containing layer within the formation. Greater pay zone thickness may indicate a greater potential volumetric production of hydrocarbon fluids. Each of the hydrocarbon containing layers may have a thickness that varies depending on, for example, conditions under which the formation hydrocarbon containing layer was formed. Therefore, an organic-rich rock formation will typically be selected for treatment if that formation includes at least one formation hydrocarbon-containing layer having a thickness sufficient for economical production of produced fluids.

[0123] An organic-rich rock formation may also be chosen if the thickness of several layers that are closely spaced together is sufficient for economical production of produced fluids. For example, an in situ conversion process for formation hydrocarbons may include selecting and treating a layer within an organic-rich rock formation having a thickness of greater than about 5 meters, 10 meters, 50 meters, or even 100 meters. In this manner, heat losses (as a fraction of total injected heat) to layers formed above and below an organic-rich rock formation may be less than such heat losses from a thin layer of formation hydrocarbons. A process as described herein, however, may also include selecting and treating layers that may include layers substantially free of formation hydrocarbons or thin layers of formation hydrocarbons.

[0124] The richness of one or more organic-rich rock formations may also be considered. Richness may depend on many factors including the conditions under which the formation hydrocarbon containing layer was formed, an amount of formation hydrocarbons in the layer, and/or a composition of formation hydrocarbons in the layer. A thin and rich formation hydrocarbon layer may be able to produce significantly more valuable hydrocarbons than a much thicker, less rich formation hydrocarbon layer. Of course, producing hydrocarbons from a formation that is both thick and rich is desirable.

[0125] The kerogen content of an organic-rich rock formation may be ascertained from outcrop or core samples using a variety of data. Such data may include organic carbon content, hydrogen index, and modified Fischer assay analyses. The Fischer Assay is a standard method which involves heating a sample of a formation hydrocarbon containing layer to approximately 500° C. in one hour, collecting fluids produced from the heated sample, and quantifying the amount of fluids produced.

[0126] Subsurface formation permeability may also be assessed via rock samples, outcrops, or studies of ground water flow. Furthermore the connectivity of the development area to ground water sources may be assessed. Thus, an organic-rich rock formation may be chosen for development based on the permeability or porosity of the formation matrix even if the thickness of the formation is relatively thin.

[0127] Other factors known to petroleum engineers may be taken into consideration when selecting a formation for development. Such factors include depth of the perceived pay zone, stratigraphic proximity of fresh ground water to kerogen-containing zones, continuity of thickness, and other factors. For instance, the assessed fluid production content within a formation will also effect eventual volumetric production.

[0128] In producing hydrocarbon fluids from an oil shale field, it may be desirable to control the migration of pyrolyzed fluids. In some instances, this includes the use of injection wells such as well **31**, particularly around the periphery of the field. Such wells may inject water, steam, CO_2, heated methane, or other fluids to drive cracked kerogen fluids inwardly towards production wells. In some embodiments, physical barriers may be placed around the area of the organic-rich rock formation under development. One example of a physical barrier involves the creation of freeze walls. Freeze walls are formed by circulating refrigerant through peripheral wells to substantially reduce the temperature of the rock formation. This, in turn, prevents the pyrolyzation of kerogen present at the periphery of the field and the outward migration of oil and gas. Freeze walls will also cause native water in the formation along the periphery to freeze.

[0129] The use of subsurface freezing to stabilize poorly consolidated soils or to provide a barrier to fluid flow is known in the art. Shell Exploration and Production Company has discussed the use of freeze walls for oil shale production in several patents, including U.S. Pat. No. 6,880,633 and U.S. Pat. No. 7,032,660. Shell's '660 patent uses subsurface freezing to protect against groundwater flow and groundwater contamination during in situ shale oil production. Additional patents that disclose the use of so-called freeze walls are U.S. Pat. No. 3,528,252, U.S. Pat. No. 3,943,722, U.S. Pat. No. 3,729,965, U.S. Pat. No. 4,358,222, U.S. Pat. No. 4,607,488, and WO Pat. No. 98996480.

[0130] As noted above, several different types of wells may be used in the development of an organic-rich rock formation, including, for example, an oil shale field. For example, the heating of the organic-rich rock formation may be accomplished through the use of heater wells. The heater wells may include, for example, electrical resistance heating elements. The production of hydrocarbon fluids from the formation may be accomplished through the use of wells completed for the production of fluids. The injection of an aqueous fluid may be accomplished through the use of injection wells. Finally, the production of an aqueous solution may be accomplished through use of solution production wells.

[0131] The different wells listed above may be used for more than one purpose. Stated another way, wells initially completed for one purpose may later be used for another purpose, thereby lowering project costs and/or decreasing the time required to perform certain tasks. For example, one or more of the production wells may also be used as injection wells for later injecting water into the organic-rich rock formation. Alternatively, one or more of the production wells may also be used as solution production wells for later producing an aqueous solution from the organic-rich rock formation.

[0132] In other aspects, production wells (and in some circumstances heater wells) may initially be used as dewatering wells (e.g., before heating is begun and/or when heating is initially started). In addition, in some circumstances dewatering wells can later be used as production wells (and in some circumstances heater wells). As such, the dewatering wells may be placed and/or designed so that such wells can be later used as production wells and/or heater wells. The heater wells may be placed and/or designed so that such wells can be later used as production wells and/or dewatering wells. The production wells may be placed and/or designed so that such wells can be later used as dewatering wells and/or heater wells. Similarly, injection wells may be wells that initially were used for other purposes (e.g., heating, production, dewatering, monitoring, etc.), and injection wells may later be used for other purposes. Similarly, monitoring wells may be wells that initially were used for other purposes (e.g., heating, production, dewatering, injection, etc.). Finally, monitoring wells may later be used for other purposes such as water production.

[0133] It is desirable to arrange the various wells for an oil shale field in a pre-planned pattern. For instance, heater wells may be arranged in a variety of patterns including, but not limited to triangles, squares, hexagons, and other polygons. The pattern may include a regular polygon to promote uniform heating through at least the portion of the formation in which the heater wells are placed. The pattern may also be a line drive pattern. A line drive pattern generally includes a first linear array of heater wells, a second linear array of heater wells, and a production well or a linear array of production wells between the first and second linear array of heater wells. Interspersed among the heater wells are typically one or more production wells. The injection wells may likewise be disposed within a repetitive pattern of units, which may be similar to or different from that used for the heater wells.

[0134] One method to reduce the number of wells is to use a single well as both a heater well and a production well. Reduction of the number of wells by using single wells for sequential purposes can reduce project costs. One or more monitoring wells may be disposed at selected points in the field. The monitoring wells may be configured with one or more devices that measure a temperature, a pressure, and/or a property of a fluid in the wellbore. In some instances, a heater well may also serve as a monitoring well, or otherwise be instrumented.

[0135] Another method for reducing the number of heater wells is to use well patterns. Regular patterns of heater wells equidistantly spaced from a production well may be used. The patterns may form equilateral triangular arrays, hexagonal arrays, or other array patterns. The arrays of heater wells may be disposed such that a distance between each heater well is less than about 70 feet (21 meters). A portion of the formation may be heated with heater wells disposed substantially parallel to a boundary of the hydrocarbon formation.

[0136] In alternative embodiments, the array of heater wells may be disposed such that a distance between each heater well may be less than about 100 feet, or 50 feet, or 30 feet. Regardless of the arrangement of or distance between the heater wells, in certain embodiments, a ratio of heater wells to production wells disposed within a organic-rich rock formation may be greater than about 5, 8, 10, 20, or more.

[0137] In one embodiment, individual production wells are surrounded by at most one layer of heater wells. This may include arrangements such as 5-spot, 7-spot, or 9-spot arrays, with alternating rows of production and heater wells. In another embodiment, two layers of heater wells may surround a production well, but with the heater wells staggered so that a clear pathway exists for the majority of flow away from the further heater wells. Flow and reservoir simulations may be employed to assess the pathways and temperature history of hydrocarbon fluids generated in situ as they migrate from their points of origin to production wells.

[0138] FIG. **4** provides a plan view of an illustrative heater well arrangement using more than one layer of heater wells. The heater well arrangement is used in connection with the production of hydrocarbons from a shale oil development area **400**. In FIG. **4**, the heater well arrangement employs a first layer of heater wells **410**, surrounded by a second layer of heater wells **420**. The heater wells in the first layer **410** are referenced at **431**, while the heater wells in the second layer **420** are referenced at **432**.

[0139] A production well **440** is shown central to the well layers **410** and **420**. It is noted that the heater wells **432** in the second layer **420** of wells are offset from the heater wells **431** in the first layer **410** of wells, relative to the production well **440**. The purpose is to provide a flowpath for converted hydrocarbons that minimizes travel near a heater well in the first layer **410** of heater wells. This, in turn, minimizes secondary cracking of hydrocarbons converted from kerogen as hydrocarbons flow from the second layer of wells **420** to the production wells **440**.

[0140] In the illustrative arrangement of FIG. **4**, the first layer **410** and the second layer **420** each defines a 5-spot pattern. However, it is understood that other patterns may be employed, such as 3-spot or 6-spot patterns. In any instance, a plurality of heater wells **431** comprising a first layer of heater wells **410** is placed around a production well **440**, with a second plurality of heater wells **432** comprising a second layer of heater wells **420** placed around the first layer **410**.

[0141] The heater wells in the two layers also may be arranged such that the majority of hydrocarbons generated by heat from each heater well **432** in the second layer **420** are able to migrate to a production well **440** without passing substantially near a heater well **431** in the first layer **410**. The heater wells **431**, **432** in the two layers **410**, **420** further may be arranged such that the majority of hydrocarbons generated by heat from each heater well **432** in the second layer **420** are able to migrate to the production well **440** without passing through a zone of substantially increasing formation temperature.

[0142] Another method for reducing the number of heater wells is to use well patterns that are elongated in a particular direction, particularly in a direction determined to provide the most efficient thermal conductivity. Heat convection may be affected by various factors such as bedding planes and stresses within the formation. For instance, heat convection may be more efficient in the direction perpendicular to the least horizontal principal stress on the formation. In some instances, heat convection may be more efficient in the direction parallel to the least horizontal principal stress. Elongation may be practiced in, for example, line drive patterns or spot patterns.

[0143] In connection with the development of a shale oil field, it may be desirable that the progression of heat through the subsurface in accordance with steps **130** and **135** be uniform. However, for various reasons the heating and maturation of formation hydrocarbons in a subsurface formation may not proceed uniformly despite a regular arrangement of heater and production wells. Heterogeneities in the oil shale properties and formation structure may cause certain local areas to be more or less efficient in terms of pyrolysis. Moreover, formation fracturing which occurs due to the heating and maturation of the oil shale can lead to an uneven distribution of preferred pathways and, thus, increase flow to certain production wells and reduce flow to others. Uneven fluid maturation may be an undesirable condition since certain subsurface regions may receive more heat energy than necessary where other regions receive less than desired. This, in turn, leads to the uneven flow and recovery of production fluids. Produced oil quality, overall production rate, and/or ultimate recoveries may be reduced.

[0144] To detect uneven flow conditions, production and heater wells may be instrumented with sensors. Sensors may include equipment to measure temperature, pressure, flow rates, and/or compositional information. Data from these sensors can be processed via simple rules or input to detailed simulations to reach decisions on how to adjust heater and production wells to improve subsurface performance. Production well performance may be adjusted by controlling backpressure or throttling on the well. Heater well performance may also be adjusted by controlling energy input. Sensor readings may also sometimes imply mechanical problems with a well or downhole equipment which requires repair, replacement, or abandonment.

[0145] In one embodiment, flow rate, compositional, temperature and/or pressure data are utilized from two or more wells as inputs to a computer algorithm to control heating rate and/or production rates. Unmeasured conditions at or in the neighborhood of the well are then estimated and used to control the well. For example, in situ fracturing behavior and kerogen maturation are estimated based on thermal, flow, and compositional data from a set of wells. In another example, well integrity is evaluated based on pressure data, well temperature data, and estimated in situ stresses. In a related embodiment the number of sensors is reduced by equipping only a subset of the wells with instruments, and using the results to interpolate, calculate, or estimate conditions at uninstrumented wells. Certain wells may have only a limited set of sensors (e.g., wellhead temperature and pressure only) where others have a much larger set of sensors (e.g., wellhead temperature and pressure, bottomhole temperature and pressure, production composition, flow rate, electrical signature, casing strain, etc.).

[0146] As noted above, there are various methods for applying heat to an organic-rich rock formation. For example, one method may include electrical resistance heaters disposed in a wellbore or outside of a wellbore. One such method involves the use of electrical resistive heating elements in a cased or uncased wellbore. Electrical resistance heating involves directly passing electricity through a conductive material such that resistive losses cause it to heat the conductive material. Other heating methods include the use of downhole combustors, in situ combustion, radio-frequency (RF) electrical energy, or microwave energy. Still others include injecting a hot fluid into the oil shale formation to directly heat it. The hot fluid may or may not be circulated.

[0147] One method for formation heating involves the use of electrical resistors in which an electrical current is passed through a resistive material which dissipates the electrical energy as heat. This method is distinguished from dielectric heating in which a high-frequency oscillating electric current induces electrical currents in nearby materials and causes them to heat. The electric heater may include an insulated conductor, an elongated member disposed in the opening, and/or a conductor disposed in a conduit. An early patent disclosing the use of electrical resistance heaters to produce oil shale in situ is U.S. Pat. No. 1,666,488. The '488 patent issued to Crawshaw in 1928. Since 1928, various designs for downhole electrical heaters have been proposed. Illustrative designs are presented in U.S. Pat. No. 1,701,884, U.S. Pat. No. 3,376,403, U.S. Pat. No. 4,626,665, U.S. Pat. No. 4,704,514, and U.S. Pat. No. 6,023,554).

[0148] A review of application of electrical heating methods for heavy oil reservoirs is given by R. Sierra and S. M. Farouq Ali, "Promising Progress in Field Application of Reservoir Electrical Heating Methods", Society of Petroleum Engineers Paper 69709, 2001. The entire disclosure of this reference is hereby incorporated by reference.

[0149] Certain previous designs for in situ electrical resistance heaters utilized solid, continuous heating elements (e.g., metal wires or strips). However, such elements may lack the necessary robustness for long-term, high temperature applications such as oil shale maturation. As the formation heats and the oil shale matures, significant expansion of the rock occurs. This leads to high stresses on wells intersecting the formation. These stresses can lead to bending and stretching of the wellbore pipe and internal components. Cementing (e.g., U.S. Pat. No. 4,886,118) or packing (e.g., U.S. Pat. No. 2,732,195) a heating element in place may provide some protection against stresses, but some stresses may still be transmitted to the heating element.

[0150] Although the above processes are applied in these examples to generate hydrocarbons from oil shale, the idea may also be applicable to heavy oil reservoirs, tar sands, or gas hydrates. In these instances, the electrical heat supplied would serve to reduce hydrocarbon viscosity or to melt hydrates. U.S. Pat. No. 6,148,911 discusses the use of an electrically conductive proppant to release gas from a hydrate formation. It is also known to apply a voltage across a formation using brine as the electrical conductor and heating element. However, it is believed that the use of formation brine as a heating element is inadequate for shale conversion as it is limited to temperatures below the in situ boiling point of water. Thus, the circuit fails when the water vaporizes.

[0151] The purpose for heating the organic-rich rock formation is to pyrolyze at least a portion of the solid formation hydrocarbons to create hydrocarbon fluids. The solid formation hydrocarbons may be pyrolyzed in situ by raising the organic-rich rock formation, (or zones within the formation), to a pyrolyzation temperature. In certain embodiments, the temperature of the formation may be slowly raised through the pyrolysis temperature range. For example, an in situ conversion process may include heating at least a portion of the organic-rich rock formation to raise the average temperature of the zone above about 270° C. at a rate less than a selected amount (e.g., about 10° C., 5° C.; 3° C., 1° C., 0.5° C., or 0.1° C.) per day. In a further embodiment, the portion may be heated such that an average temperature of the selected zone may be less than about 375° C. or, in some embodiments, less than about 400° C. The formation may be heated such that a temperature within the formation reaches (at least) an initial pyrolyzation temperature, that is, a temperature at the lower end of the temperature range where pyrolyzation begins to occur.

[0152] The pyrolysis temperature range may vary depending on the types of formation hydrocarbons within the formation, the heating methodology, and the distribution of heating sources. For example, a pyrolysis temperature range may include temperatures between about 270° C. and about 900° C. Alternatively, the bulk of the target zone of the formation may be heated to between 300° to 600° C. In an alternative embodiment, a pyrolysis temperature range may include temperatures between about 270° C. to about 500° C.

[0153] Preferably, for in situ processes the heating of a production zone takes place over a period of months, or even four or more years. Alternatively, the formation may be heated for one to fifteen years, alternatively, 3 to 10 years, 1.5 to 7 years, or 2 to 5 years. The bulk of the target zone of the formation may be heated to between 270° to 800° C. Preferably, the bulk of the target zone of the formation is heated to between 300° to 600° C. Alternatively, the bulk of the target zone is ultimately heated to a temperature below 400° C. (752° F.).

[0154] In the production of oil and gas resources, it may be desirable to use the produced hydrocarbons as a source of power for ongoing operations. This may be applied to the development of oil and gas resources from oil shale. In this respect, when electrically resistive heaters are used in connection with in situ shale oil recovery, large amounts of power are required.

[0155] Electrical power may be obtained from turbines that turn generators. It may be economically advantageous to power the gas turbines by utilizing produced gas from the field. However, such produced gas must be carefully controlled so not to damage the turbine, cause the turbine to misfire, or generate excessive pollutants (e.g., NO_x).

[0156] One source of problems for gas turbines is the presence of contaminants within the fuel. Contaminants include solids, water, heavy components present as liquids, and hydrogen sulfide. Additionally, the combustion behavior of the fuel is important. Combustion parameters to consider include heating value, specific gravity, adiabatic flame temperature, flammability limits, autoignition temperature, autoignition delay time, and flame velocity. Wobbe Index (WI) is often used as a key measure of fuel quality. WI is equal to the ratio of the lower heating value to the square root of the gas specific gravity. Control of the fuel's Wobbe Index to a target value and range of, for example, 10% or 20% can allow simplified turbine design and increased optimization of performance.

[0157] Fuel quality control may be useful for shale oil developments where the produced gas composition may change over the life of the field and where the gas typically has significant amounts of CO_2, CO, and H_2 in addition to light hydrocarbons. Commercial scale oil shale retorting is expected to produce a gas composition that changes with time.

[0158] Inert gases in the turbine fuel can increase power generation by increasing mass flow while maintaining a flame temperature in a desirable range. Moreover inert gases can lower flame temperature and thus reduce NO_x pollutant generation. Gas generated from oil shale maturation may have significant CO_2 content. Therefore, in certain embodiments of the production processes, the CO_2 content of the fuel gas is adjusted via separation or addition in the surface facilities to optimize turbine performance.

[0159] Achieving a certain hydrogen content for low-BTU fuels may also be desirable to achieve appropriate burn properties. In certain embodiments of the processes herein, the H_2 content of the fuel gas is adjusted via separation or addition in the surface facilities to optimize turbine performance. Adjustment of H_2 content in non-shale oil surface facilities utilizing low BTU fuels has been discussed in the patent literature (e.g., U.S. Pat. No. 6,684,644 and U.S. Pat. No. 6,858,049, the entire disclosures of which are hereby incorporated by reference).

[0160] As noted, the process of heating formation hydrocarbons within an organic-rich rock formation, for example, by pyrolysis, may generate fluids. The heat-generated fluids may include water which is vaporized within the formation. In addition, the action of heating kerogen produces pyrolysis fluids which tend to expand upon heating. The produced pyrolysis fluids may include not only water, but also, for example, hydrocarbons, oxides of carbon, ammonia, molecular nitrogen, and molecular hydrogen. Therefore, as temperatures within a heated portion of the formation increase, a pressure within the heated portion may also increase as a result of increased fluid generation, molecular expansion, and vaporization of water. Thus, some corollary exists between subsurface pressure in an oil shale formation and the fluid pressure generated during pyrolysis. This, in turn, indicates that formation pressure may be monitored to detect the progress of a kerogen conversion process.

[0161] The pressure within a heated portion of an organic-rich rock formation depends on other reservoir characteristics. These may include, for example, formation depth, distance from a heater well, a richness of the formation hydrocarbons within the organic-rich rock formation, the degree of heating, and/or a distance from a producer well.

[0162] It may be desirable for the developer of an oil shale field to monitor formation pressure during development. Pressure within a formation may be determined at a number of different locations. Such locations may include, but may not be limited to, at a wellhead and at varying depths within a wellbore. In some embodiments, pressure may be measured at a producer well. In an alternate embodiment, pressure may be measured at a heater well. In still another embodiment, pressure may be measured downhole of a dedicated monitoring well.

[0163] The process of heating an organic-rich rock formation to a pyrolysis temperature range not only will increase formation pressure, but will also increase formation permeability. The pyrolysis temperature range should be reached before substantial permeability has been generated within the organic-rich rock formation. An initial lack of permeability may prevent the transport of generated fluids from a pyrolysis zone within the formation. In this manner, as heat is initially transferred from a heater well to an organic-rich rock formation, a fluid pressure within the organic-rich rock formation may increase proximate to that heater well. Such an increase in fluid pressure may be caused by, for example, the generation of fluids during pyrolysis of at least some formation hydrocarbons in the formation.

[0164] Alternatively, pressure generated by expansion of pyrolysis fluids or other fluids generated in the formation may be allowed to increase. This assumes that an open path to a production well or other pressure sink does not yet exist in the formation. In one aspect, a fluid pressure may be allowed to increase to or above a lithostatic stress. In this instance, fractures in the hydrocarbon containing formation may form when the fluid pressure equals or exceeds the lithostatic stress. For example, fractures may form from a heater well to a production well. The generation of fractures within the heated portion may reduce pressure within the portion due to the production of produced fluids through a production well.

[0165] Once pyrolysis has begun within an organic-rich rock formation, fluid pressure may vary depending upon various factors. These include, for example, thermal expansion of hydrocarbons, generation of pyrolysis fluids, rate of conversion, and withdrawal of generated fluids from the formation. For example, as fluids are generated within the formation, fluid pressure within the pores may increase. Removal of generated fluids from the formation may then decrease the fluid pressure within the near wellbore region of the formation.

[0166] In certain embodiments, a mass of at least a portion of an organic-rich rock formation may be reduced due, for example, to pyrolysis of formation hydrocarbons and the production of hydrocarbon fluids from the formation. As such, the permeability and porosity of at least a portion of the formation may increase. Any in situ method that effectively produces oil and gas from oil shale will create permeability in what was originally a very low permeability rock. The extent to which this will occur is illustrated by the large amount of expansion that must be accommodated if fluids generated from kerogen are unable to flow. The concept is illustrated in FIG. **5**.

[0167] FIG. **5** provides a bar chart comparing one ton of Green River oil shale before **50** and after **51** a simulated in situ, retorting process. The simulated process was carried out at 2,400 psi and 750° F. (about 400° C.) on oil shale having a total organic carbon content of 22 wt. % and a Fisher assay of 42 gallons/ton. Before the conversion, a total of 16.5 ft^3 of rock matrix **52** existed. This matrix comprised 8.4 ft^3 of mineral **53**, i.e., dolomite, limestone, etc., and 8.1 ft^3 of kerogen **54** imbedded within the shale. As a result of the conversion the material expanded to 27.3 ft^3 **55**. This represented 8.4 ft^3 of mineral **56** (the same number as before the conversion), 6.6 ft^3 of hydrocarbon liquid 57, 9.4 ft^3 of hydrocarbon vapor 58, and 2.9 ft^3 of coke **59**. It can be seen that substantial volume expansion occurred during the conversion process. This, in turn, increases permeability of the rock structure.

[0168] FIG. **6** illustrates a schematic diagram of an embodiment of surface facilities **70** that may be configured to treat a produced fluid. The produced fluid **85** produced from a subsurface formation, shown schematically at **84**, though a production well **71**. The produced fluid **85** may include any of the produced fluids produced by any of the methods as described herein. The subsurface formation **84** may be any subsurface formation including, for example, an organic-rich rock formation containing any of oil shale, coal, or tar sands for example. In the illustrative surface facilities **70**, the produced fluids are quenched **72** to a temperature below 300° F., 200° F., or even 100° F. This serves to separate out condensable components (i.e., oil **74** and water **75**).

[0169] Produced fluids **85** from in situ oil shale production contain a number of components which may be separated in the surface facilities **70**. The produced fluids **85** typically contain water **78**, noncondensable hydrocarbon alkane species (e.g., methane, ethane, propane, n-butane, isobutane), noncondensable hydrocarbon alkene species (e.g., ethene, propene), condensable hydrocarbon species composed of (alkanes, olefins, aromatics, and polyaromatics among others), CO_2, CO, H_2, H_2S, and NH_3. In a surface facility such as facility **70**, condensable components **74** may be separated from non-condensable components **76** by reducing temperature and/or increasing pressure. Temperature reduction may be accomplished using heat exchangers cooled by ambient air or available water **72**. Alternatively, the hot produced fluids may be cooled via heat exchange with produced hydrocarbon fluids previously cooled. The pressure may be increased via centrifugal or reciprocating compressors. Alternatively, or in conjunction, a diffuser-expander apparatus may be used to condense out liquids from gaseous flows. Separations may involve several stages of cooling and/or pressure changes.

[0170] In the arrangement of FIG. **6**, the surface facilities **70** include an oil separator **73** for separating liquids, or oil **74**, from hydrocarbon vapors, or gas **76**. The noncondensable vapor components **76** are treated in a gas treating unit **77** to remove water **78** and sulfur species **79**. Heavier components are removed from the gas (e.g., propane and butanes) in a gas plant **81** to form liquid petroleum gas (LPG) **80**. The LPG **80** may be placed into a truck or line for sale. Water **78** in addition to condensable hydrocarbons **74** may be dropped out of the gas **76** when reducing temperature or increasing pressure. Liquid water may be separated from condensable hydrocarbons **74** via gravity settling vessels or centrifugal separators. Demulsifiers may be used to aid in water separation.

[0171] The surface facilities also operate to generate electrical power **82** in a power plant **88** from the remaining gas **83**. The electrical power **82** may be used as an energy source for heating the subsurface formation **84** through any of the methods described herein. For example, the electrical power **82** may be fed at a high voltage, for example 132 kV, to a transformer **86** and let down to a lower voltage, for example 6600 V, before being fed to an electrical resistance heater element **89** located in a heater well **87** in the subsurface formation **84**. In this way all or a portion of the power required to heat the subsurface formation **84** may be generated from the non-condensable portion **76** of the produced fluids **85**. Excess gas, if available, may be exported for sale.

[0172] In an embodiment, heating a portion of an organic-rich rock formation in situ to a pyrolysis temperature may increase permeability of the heated portion. For example, permeability may increase due to formation of thermal fractures within the heated portion caused by application of heat. As the temperature of the heated portion increases, water may be removed due to vaporization. The vaporized water may escape and/or be removed from the formation. In addition, permeability of the heated portion may also increase as a result of production of hydrocarbon fluids from pyrolysis of at least some of the formation hydrocarbons within the heated portion on a macroscopic scale.

[0173] Certain systems and methods described herein may be used to treat formation hydrocarbons in at least a portion of a relatively low permeability formation (e.g., in "tight" formations that contain formation hydrocarbons). Such formation hydrocarbons may be heated to pyrolyze at least some of the formation hydrocarbons in a selected zone of the formation. Heating may also increase the permeability of at least a portion of the selected zone. Hydrocarbon fluids generated from pyrolysis may be produced from the formation, thereby further increasing the formation permeability.

[0174] Permeability of a selected zone within the heated portion of the organic-rich rock formation may also rapidly increase while the selected zone is heated by conduction. For example, permeability of an impermeable organic-rich rock formation may be less than about 0.1 millidarcy before heating. In some embodiments, pyrolyzing at least a portion of organic-rich rock formation may increase permeability within a selected zone of the portion to greater than about 10 millidarcies, 100 millidarcies, 1 Darcy, 10 Darcies, 20 Darcies, or 50 Darcies. Therefore, a permeability of a selected zone of the portion may increase by a factor of more than about 10, 100, 1,000, 10,000, or 100,000. In one embodiment, the organic-rich rock formation has an initial total permeability less than 1 millidarcy, alternatively less than 0.1 or 0.01 millidarcies, before heating the organic-rich rock formation. In one embodiment, the organic-rich rock formation has a post heating total permeability of greater than 1 millidarcy, alternatively, greater than 10, 50 or 100 millidarcies, after heating the organic-rich rock formation.

[0175] In connection with the production of hydrocarbons from a rock matrix, particularly those of shallow depth, a concern may exist with respect to earth subsidence. This is particularly true in the in situ heating of organic-rich rock where a portion of the matrix itself is thermally converted and removed. Initially, the formation may contain formation hydrocarbons in solid form, such as, for example, kerogen. The formation may also initially contain water-soluble minerals. Initially, the formation may also be substantially impermeable to fluid flow.

[0176] The in situ heating of the matrix pyrolyzes at least a portion of the formation hydrocarbons to create hydrocarbon fluids. This, in turn, creates permeability within a matured (pyrolyzed) organic-rich rock zone in the organic-rich rock formation. The combination of pyrolyzation and increased permeability permits hydrocarbon fluids to be produced from the formation. At the same time, the loss of supporting matrix material also creates the potential for subsidence relative to the earth surface.

[0177] In some instances, subsidence is sought to be minimized in order to avoid environmental or hydrogeological impact. In this respect, changing the contour and relief of the earth surface, even by a few inches, can change runoff patterns, affect vegetation patterns, and impact watersheds. In addition, subsidence has the potential of damaging production or heater wells formed in a production area. Such subsidence can create damaging hoop and compressional stresses on wellbore casings, cement jobs, and equipment downhole.

[0178] In order to avoid or minimize subsidence, it is proposed to leave selected portions of the formation hydrocarbons substantially unpyrolyzed. This serves to preserve one or more unmatured, organic-rich rock zones. In some embodiments, the unmatured organic-rich rock zones may be shaped as substantially vertical pillars extending through a substantial portion of the thickness of the organic-rich rock formation.

[0179] The heating rate and distribution of heat within the formation may be designed and implemented to leave sufficient unmatured pillars to prevent subsidence. In one aspect, heat injection wellbores are formed in a pattern such that untreated pillars of oil shale are left therebetween to support the overburden and prevent subsidence.

[0180] In some embodiments, compositions and properties of the hydrocarbon fluids produced by an in situ conversion process may vary depending on, for example, conditions within an organic-rich rock formation. Controlling heat and/or heating rates of a selected section in an organic-rich rock formation may increase or decrease production of selected produced fluids.

[0181] In one embodiment, operating conditions may be determined by measuring at least one property of the organic-rich rock formation. The measured properties may be input into a computer executable program. At least one property of the produced fluids selected to be produced from the formation may also be input into the computer executable program. The program may be operable to determine a set of operating conditions from at least the one or more measured properties. The program may also be configured to determine the set of operating conditions from at least one property of the selected produced fluids. In this manner, the determined set of operating conditions may be configured to increase production of selected produced fluids from the formation.

[0182] Certain heater well embodiments may include an operating system that is coupled to any of the heater wells such as by insulated conductors or other types of wiring. The operating system may be configured to interface with the heater well. The operating system may receive a signal (e.g., an electromagnetic signal) from a heater that is representative of a temperature distribution of the heater well. Additionally, the operating system may be further configured to control the heater well, either locally or remotely. For example, the operating system may alter a temperature of the heater well by altering a parameter of equipment coupled to the heater well. Therefore, the operating system may monitor, alter, and/or control the heating of at least a portion of the formation.

[0183] In some embodiments, a heater well may be turned down and/or off after an average temperature in a formation may have reached a selected temperature. Turning down and/or off the heater well may reduce input energy costs, substantially inhibit overheating of the formation, and allow heat to substantially transfer into colder regions of the formation.

[0184] Temperature (and average temperatures) within a heated organic-rich rock formation may vary, depending on, for example, proximity to a heater well, thermal conductivity and thermal diffusivity of the formation, type of reaction occurring, type of formation hydrocarbon, and the presence of water within the organic-rich rock formation. At points in the field where monitoring wells are established, temperature measurements may be taken directly in the wellbore. Further, at heater wells the temperature of the immediately surrounding formation is fairly well understood. However, it is desirable to interpolate temperatures to points in the formation intermediate temperature sensors and heater wells.

[0185] In accordance with one aspect of the production processes of the present inventions, a temperature distribution within the organic-rich rock formation may be computed using a numerical simulation model. The numerical simulation model may calculate a subsurface temperature distribution through interpolation of known data points and assumptions of formation conductivity. In addition, the numerical simulation model may be used to determine other properties of the formation under the assessed temperature distribution. For example, the various properties of the formation may include, but are not limited to, permeability of the formation.

[0186] The numerical simulation model may also include assessing various properties of a fluid formed within an organic-rich rock formation under the assessed temperature distribution. For example, the various properties of a formed fluid may include, but are not limited to, a cumulative volume of a fluid formed in the formation, fluid viscosity, fluid density, and a composition of the fluid formed in the formation. Such a simulation may be used to assess the performance of a commercial-scale operation or small-scale field experiment. For example, a performance of a commercial-scale development may be assessed based on, but not limited to, a total volume of product that may be produced from a research-scale operation.

[0187] In the present disclosure, methods for heating a subsurface formation using electrical resistance heating are provided. The resistive heat is generated primarily from electrically conductive material injected into the formation from wellbores. An electrical current is then passed through the conductive material so that electrical energy is converted to thermal energy. The thermal energy is transported to the formation by thermal conduction to heat the organic-rich rocks.

[0188] In one preferred embodiment of the current disclosure, conductive granular material is used as a downhole heating element. The granular heating element is able to withstand geomechanical stresses created during the formation heating process. In this respect, the granular material can readily change shape as needed without losing electrical connectivity. Thus, methods are provided herein for applying heat to a subsurface formation wherein a granular material provides a resistively conductive pathway between electrically conductive members within adjacent wellbores. However, non-granular conductive material such as conductive liquids that gel in place may be used.

[0189] FIG. **7** is a perspective view of a hydrocarbon production area **700**. The hydrocarbon production area **700** includes a subsurface formation **715**. The subsurface formation **715** comprises organic-rich rock. In one instance the organic-rich rock contains kerogen.

[0190] A substantially vertical fracture **712** has been created within the subsurface formation **715**. The fracture **712** is preferably hydraulically formed. The fracture **712** is propped with particles of an electrically conductive material (not shown in FIG. **7**). In accordance with the methods herein, an electrical current is sent through the conductive material to generate resistive heat within the formation **715**.

[0191] FIG. **7** demonstrates the heat **710** emanating from the fracture **712**. In order to provide electrical current and generate the heat **710**, a voltage **714** is applied across two adjacent wells **716** and **718**. The fracture **712** intersects the wells **716**, **718** so that current travels from a first well (such as well **716**), through fracture **712**, and to a second well (such as well **718**).

[0192] Various ways of running current through the fracture **712** may be arranged. In the arrangement of FIG. **7**, an AC voltage **714** is preferred. This is because AC voltage is more readily generated and minimizes electrochemical corrosion as compared to DC voltage. However, any form of electrical energy, including without limitation, DC voltage, is suitable for use in the methods herein.

[0193] In the example of FIG. **7**, a negative pole is set up at wellbore **716** while a positive pole is set up at wellbore **718**. Each wellbore **716**, **718** has a conductive member that runs to the subsurface formation **715** to deliver current. An amount of electrical current sufficient to generate heat necessary to cause pyrolysis of solid hydrocarbons is provided. Kinetic parameters for Green River oil shale, for example, indicate that for a heating rate of 100° C. (180° F.) per year, complete kerogen conversion will occur at a temperature of about 324° C. (615° F.). Fifty percent conversion will occur at a temperature of about 291° C. (555° F.). Oil shale near the fracture will be heated to conversion temperatures within months, but it is likely to require several years to attain thermal penetration depths required for generation of economic reserves across a subsurface volume.

[0194] Within the fracture **712**, the granular material acts as a heating element. As electric current is passed through the fracture **712**, heat **710** is generated by resistive heating. Heat **710** is transferred by thermal conduction to the formation **715** surrounding the fracture **712**. As a result, the organic-rich rock within the formation **715** is heated sufficiently to convert kerogen to hydrocarbons. The generated hydrocarbons are then produced using well-known production methods.

[0195] In the arrangement of FIG. **7**, the formation **715** is shown primarily along a single vertical plane. Further, the heat **710** is shown emanating from the fracture **712** within that vertical plane. However, it is understood that the formation **715** is a three-dimensional subsurface volume, and that the heat **710** will conduct across a portion of that volume.

[0196] As described above, FIG. **7** depicts a heating process using a single vertical hydraulic fracture **712** and a pair of vertical wells **716**, **718**. In practice, a number of wellbore pairs **716**, **718** would be completed with an intersecting fracture **712**. However, other wellbore and completion arrangements may be provided. Examples include the use of horizontal wells and/or horizontal fractures. Commercial applications may involve multiple fractures with the placement of multiple wells in a pattern or line-drive formation.

[0197] During the thermal conversion process, oil shale permeability is likely to increase. This may be caused by the increased pore volume available for flow as solid kerogen is converted to liquid or gaseous hydrocarbons. Alternatively, increased permeability may result from the formation of fractures as kerogen converts to hydrocarbons and undergoes a substantial volume increase within a confined system. In this respect, if initial permeability is too low to allow release of the hydrocarbons, excess pore pressure will eventually cause fractures to develop. These are in addition to the hydraulic fractures initially formed during completion of the wellbores **716**, **718**.

[0198] Referring now to FIGS. **8**A and **8**B, alternate arrangements **800**A, **800**B for heating a subsurface formation are illustrated. First, FIG. **8**A shows a hydrocarbon production area **805**A that includes a subsurface formation **815**. The subsurface formation **815** comprises organic-rich rock. An example of such an organic-rich rock is oil shale.

[0199] In the arrangement of FIG. **8**A, a first plurality of wellbores **816** is provided. Each wellbore **816** has a vertical portion and a deviated, substantially horizontal portion. Heat is once again delivered via a plurality of hydraulic fractures propped with particles of an electrically conductive material. The fractures are shown at **812** and are substantially vertical. Each hydraulic fracture **812** is longitudinal (or runs along) the horizontal portion of the wells **816**.

[0200] A separate second plurality of wells **818** is also provided in the hydrocarbon production area **800**A. These wells **818** also have a substantially vertical portion and a substantially horizontal portion. The substantially horizontal portions of the respective wells **818** intersect respective fractures **812**.

[0201] In the arrangement of FIG. **8**A, a voltage is applied across pairs of wells from the first plurality **816** and the second plurality **818** of wells. The wells **816** in the first plurality of wells comprise negative poles while the wells **818** in the second plurality of wells comprise positive poles. Of course, the reverse could also be established. A voltage **814** is applied across respective wells **816**, **818** that penetrate the fractures **812**. Once again, an AC voltage **814** is preferred. However, any form of electrical energy, including without limitation, DC voltage, is suitable for use in this invention.

[0202] The pairs of wells from the respective pluralities of wells **816**, **818** make up individual electrical circuits. The circuits are "completed" by placing conductive granular material within the fractures **812**. This, in turn, generates heat via resistive heating. This heat is transferred by thermal conduction to organic-rich rock within the subsurface formation **815**. As a result, the organic-rich rock is heated sufficiently to convert kerogen contained in the subsurface formation **815** to hydrocarbons. The generated hydrocarbons are then produced through production wells (not shown).

[0203] It is noted that the fractures **812** in FIG. **8**A are vertical. Reciprocally, the intersecting portion of the second plurality of wellbores **818** is horizontal. However, it is understood that this arrangement could be reversed. This means that the fractures **812** may be horizontal while the intersecting portion of the second plurality of wellbores **818** is vertical. In this latter arrangement it would not be necessary for the second plurality of wellbores **818** to be deviated. As a practical matter, the orientation of the fractures may be dependent on the depth of the subsurface formation. For example, some Green River oil shale formations completed at or above 1,000 feet tend to create horizontal fractures while formations completed below about 1,000 feet tend to create vertical fractures. This, of course, is highly dependent on the actual location and the geomechanical forces at work.

[0204] FIG. **8**B shows a second hydrocarbon production area **805**B that includes a subsurface formation **815**. The subsurface formation **815** comprises organic-rich rock which may include kerogen. In the arrangement of FIG. **8**B, a first plurality of wellbores **826** is provided. Each wellbore **826** has a vertical portion and a deviated, substantially horizontal portion. Heat is once again delivered via a plurality of hydraulic fractures propped with particles of an electrically conductive material. The fractures are shown at **812** and are substantially vertical. Each hydraulic fracture **812** is longitudinal (or runs along) the horizontal portion of the wells **826**.

[0205] A separate second plurality of wells **828** is also provided in the hydrocarbon production area **800**B. These wells **818** also have a substantially vertical portion and a substantially horizontal portion. The substantially vertical portions of the respective wells **828** intersect respective fractures **812**.

[0206] In the arrangement of FIG. **8**B, a voltage is applied across the first plurality of wells **826** to one of the second plurality of wells **828**. The wells **826** in the first plurality of wells may comprise positive poles while the second well **828** may comprise a negative pole. Of course, the reverse could also be established. A voltage **824** is applied across respective wells **826**, **828** that penetrate the fractures **812**. Once again, an AC voltage **824** is preferred. However, any form of electrical energy, including without limitation, DC voltage, is suitable for use in this invention.

[0207] The wells **826**, **828** work together to make up individual electrical circuits. The circuits are "completed" by placing conductive granular material within the fractures **812**. This, in turn, generates heat via resistive heating. This heat is transferred by thermal conduction to organic-rich rock within the subsurface formation **815**. As a result, the organic-rich rock is heated sufficiently to convert kerogen contained in the subsurface formation **815** to hydrocarbons. The generated hydrocarbons are then produced through production wells (not shown).

[0208] It is noted that the fractures **812** in FIG. **8**B are vertical. Reciprocally, the intersecting portion of the second plurality of wellbores **828** is horizontal. In the production area **800**B, the horizontal portion of the second wellbores **828** intersect fractures **812** associated with more than one fracture **812** from more than one horizontal portion of the respective first wellbores **826**.

[0209] In either of production areas **800**A, **800**B, various materials may be used as the electrically conductive granular material. First, sands having a thin metal coating may be employed. Second, composite metal and ceramic materials may be used. Third, carbon-based materials may be employed. Each of these examples is not only conductive but also serves as a proppant. Several additional conductive materials may be used which are less desirable as proppants. One example is a conductive cement. Also, green or black silicon carbide, boron carbide, or calcined petroleum coke may be used as a proppant. It is also noted that combinations of the above materials may be utilized. In this respect, the electrically conductive material is not required to be homogeneous, but may comprise a mixture of two or more suitable electrically conductive materials. For example, one or more conductive materials that serve as proppants may be mixed with one or more conductive materials that are non-proppants in order to achieve a desired conductivity while operating within a designated budget.

[0210] Regardless of the composition, the conductive material preferably meets several criteria. First, the electrical resistivity of the granular material under anticipated in situ stresses is preferably high enough to provide resistive heating while also being low enough to conduct the planned electric current from one well to another. The granular material also preferably meets the usual criteria for fracture proppants, e.g., sufficient strength to hold the fracture open, and a low enough density to be pumped into the fracture. Lastly, economic application of the process may set an upper limit on the cost of an acceptable granular material.

[0211] In each of production areas **800**A, **800**B, production wells are provided. Illustrative production wells **840** are shown in FIG. **8**B. The production wells **840** are completed in the subsurface formation **815** to transport hydrocarbon fluids to the surface.

Example

[0212] In order to demonstrate the transmission of current through a fracture in an organic-rich rock in order to generate resistive heat, a laboratory test was conducted. Test results showed that resistive heating using granular material successfully transforms kerogen in a laboratory specimen of rock into producible hydrocarbons.

[0213] Referring now to FIG. **9** and FIG. **10**, a core sample **900** was taken from a kerogen-containing subterranean formation. The core sample **900** was a three-inch long plug of oil shale with a diameter of 1.39 inches. The bedding of the oil shale was perpendicular to the core **900** axis. As illustrated in FIG. **9**, core sample **900** was cut into two portions **932** and **934**. Upper face **936** lies on portion **932** while lower face **938** corresponds to portion **934**.

[0214] A tray **935** having a depth of about 0.25 mm (1/16 inch) was milled into sample portion **932** and a proxy proppant material **910** comprising #**170** cast steel shot having a diameter of about 0.1 mm (0.02 inch) was placed in the tray **935**. As illustrated, a sufficient quantity of conductive proppant material **910** to substantially fill tray **935** was used.

[0215] Electrodes **937** were placed at opposing ends of portion **932**. The electrodes **937** extend from outside the bounds of the core **900** into contact with proppant material **910**.

[0216] As shown in FIG. **10**, sample portions **932** and **934** were placed in contact as if to reconstruct the core sample **900**. The core **900** was then placed in a stainless steel sleeve **940** with portions **932** and **934** being held together with three stainless steel hose clamps **942**.

[0217] The hose clamps **942** were tightened to apply stress to the proxy proppant (seen in FIG. **9**), just as the proppant **910** would be required to support in situ stresses in a real application. The resistance between electrodes **937** was measured at 822 ohms before any electrical current was applied.

[0218] A small hole (not shown) was drilled in one half of the sample **900** in order to accommodate a thermocouple. The thermocouple was used to measure the temperature in the core sample **900** during heating. The thermocouple was positioned roughly mid-way between tray **935** and the outer diameter of core sample **900**.

[0219] The clamped core sample **900** was placed in a pressure vessel (not shown in the Figures) with a glass liner. The purpose of the glass liner was to collect hydrocarbons generated from the heating process. The pressure vessel was equipped with electrical feeds. The pressure vessel was evacuated and charged with Argon at 500 psi to provide a chemically inert atmosphere for the experiment. Electrical current in the range of 18 to 19 amps was applied between electrodes **937** for 5 hours. The thermocouple in core sample **900** measured a temperature of 268° C. after about one hour, and thereafter tapered off to about 250° C. The high temperature reached at the location of tray **935** was inferred to be from about 350° C. to about 400° C.

[0220] After the experiment was completed and the core sample **900** had cooled to ambient temperature, the pressure vessel was opened. 0.15 ml of oil was recovered from the bottom of the glass liner in which the experiment was conducted. The core sample **900** was removed from the pressure vessel, and the resistance between electrodes **937** was again measured. This post-experiment resistance measurement was 49 ohms.

[0221] During the heating period the power consumption, electrical resistance and temperature at the thermocouple embedded in the sample **900** were recorded. FIG. **11** provides graphs showing power consumption **1112**, temperature **1122**, and electrical resistance **1132** recorded as a function of time.

[0222] First, FIG. **11** includes chart **1110**. Chart **1110** has ordinate **1112** representing the electrical power, in watts, consumed during the experiment. Chart **1110** also has abscissa **1114**, which shows the elapsed time in minutes for the experiment. The total time on the abscissa **1114** was 5 hours (300 minutes). It can be seen from chart **1110** that after one hour, power applied to the core sample **900** ranged between 50 and 60 watts.

[0223] Next, FIG. **11** includes chart **1120**. Chart **1120** has ordinate **1122** representing the temperature in degrees Celsius measured at the thermocouple in the core sample **900** (FIGS. **9** and **10**) throughout the experiment. Chart **1120** also has abscissa **1124** which shows the elapsed time in minutes during the experiment. Again, the total time is 5 hours. It is noted that the temperature **1122** reached a maximum value of 268 C during the experiment. From this value it can be inferred that the temperature along the tray **935** should have reached a value of 350-400 C. This value is sufficient to cause pyrolysis.

[0224] Finally, FIG. **11** includes chart **1130**. Chart **1130** has ordinate **1132** representing the resistance in ohms measured between electrodes **937** (FIGS. **9** and **10**) during the experiment. Chart **1130** also has abscissa **1134** which again shows the elapsed time in minutes during the experiment. Only resistance measurements made during the heating experiment are included in chart **1130**. Of interest, after the initial heat-up of the sample **900**, the resistance **1132** remained relatively constant between 0.15 and 0.2 ohms. At no time during the experiment was a loss of electrical continuity observed. The pre-experiment and post-experiment resistance measurements (822 and 49 ohms) are omitted.

[0225] After the core sample **900** cooled to ambient temperature, it was removed from the pressure vessel and disassembled. The conductive proppant material **910** was observed to be impregnated in several places with tar-like hydrocarbons or bitumen, which were generated from the oil shale during the experiment. A cross section was taken through a crack that developed in the core sample **900** due to thermal expansion during the experiment. A crescent shaped section of converted oil shale adjacent to the proxy proppant **910** was observed.

[0226] Returning now to FIGS. **7**, **8**A and **8**B, connections to the fracture heating element may be implemented in various ways. In each of these arrangements, connection points are provided between conductive metal devices along adjacent wellbores to intermediate conductive granular material within a fracture. Such point connections are made along vertical wellbores (FIG. **7**), at the heel of a horizontal wellbore portion (FIG. **8**A), at the toe of a horizontal wellbore portion (FIG. **8**B).

[0227] A concern arises with respect to each of these resistive heater-well completion arrangements **700**, **800**A, **800**B. This concern relates to the potential for very high electric current density in the area where the wellbores intersect the conductive granular material. This concern applies to any of the completion arrangements of FIGS. **7**, **8**A and **8**B.

[0228] Electric current is an average quantity that describes the flow of electrons along a flow path. The SI unit for quantity of electricity or electrical charge is the coulomb. The coulomb is defined as the quantity of charge that has passed through the cross-section of an electrical conductor carrying one ampere within one second. The symbol Q is often used to denote a quantity of electricity or charge.

[0229] Electric current may have a current density representing the electric current per unit area of cross section. In SI units, this may be expressed as Amperes/m^2. A current density vector may be denoted as i and described mathematically:

$$i=nqv_d=Dv_d$$

[0230] where

[0231] i=current density vector (amperes/m^2)

[0232] n=particle density in count per volume (m^{-3});

[0233] q=individual particles' charge (coulombs);

[0234] D=charge density (Coulombs/m^3), or n q; and

[0235] v_d=particles' average drift velocity (m/sec).

[0236] The presence of excessive current density at electrical contact points downhole may result in an inconsistent heat distribution within a subsurface formation **715** or **815**. In this respect, significant heating may occur primarily near the intersection of the wellbores with the granular material, leaving inadequate resistive heating within the remainder of the subsurface formation.

[0237] To address this issue, it is proposed herein to place a second type of granular material at or near the contact points downhole. This second type of granular material has an electrical conductivity that is different from the conductive granular material in the bulk of the fracture. Such an arrangement may operate in either of two ways. If the second material has a higher conductivity, it can operate by lowering the voltage drop across a contact point having a high current density. In this instance the high current density still exists but it does not lead to excessive local heat generation. Alternatively, if the second material has a much lower (even zero) conductivity, it can operate by changing the dominant current pathways to eliminate the area of high current density.

[0238] It is preferred to employ the first option wherein the second conductive material has a significantly higher conductivity than the conductive material in the bulk of the fracture. Preferably, the conductivity of the second conductive material is about ten to 100 times higher than the conductivity of the granular material. In one aspect, the bulk of a fracture is filled with calcined coke, while the conductive material immediately at the connection point comprises powdered metals, graphite, carbon black, or combinations thereof. Examples of powdered metals include powdered copper and steel.

[0239] For example, in an exemplary embodiment of the first option, e.g., where the second conductive material has a significantly higher conductivity than the conductive material in the bulk of the fracture, the present inventors have determined that granular mixtures of graphite with up to 50% by weight cement produce suitable resistivities. The present inventors have determined that mixtures within this compositional range are also 10-100 times more conductive than the granular proppant material. The present inventors have also determined that compositions with cement content above 50% by weight increase mixture resistivity above a preferred resistivity range. Water, which may be added to control the viscosity of the granular mixture, is typically added to the granular mixture to aid in adequate distribution of the conductive material into a proppant filled fracture. The pack thickness of the injected granular material may also be controlled by addition or subtraction of water to the granular mixture, e.g., more water will produce a thinner and more widely dispersed pack upon injection. Accordingly, the present inventors have determined that the granular mixtures within the aforementioned compositional ranges are conductive enough to not generate hot spots if used as the above-described second conductive material.

[0240] For example, an exemplary composition for the above-described second conductive material that has been determined to be suitable for use in the vicinity of electrical contact points downhole includes 10 g graphite (75% dry wt.), 3.3 g Portland cement (25% wt.), and 18 g water. In order to determine the differences in bulk resistivity between a first conductive material (representative of material within the fracture and intermediate to any electrical connections) and a second conductive material (the aforementioned mixture of 10 g graphite, 3.3 g Portland cement, and 18 g of water were injected between two marble slabs subjected to various loads and stress cured for 64 hours. The overall pack thickness of the second conductive material achieved was approximately 0.01" to approximately 0.028." The resistivity of the second conductive material was approximately 0.1638 ohm cm, which was approximately 10-100 times more conductive than the surrounding proppant. The resistivity of two representative samples of the second conductive material are shown below under various loads in Table I. Sample A included a 25% by dry weight cement and 75% by dry weight graphite, and sample B included a 50% by dry weight cement and 50% by dry weight graphite. The resistivity of sample A was consistently lower than that of the second sample across all subjected loads. While adequate resistivities were achieved in both samples, a preferred embodiment would include a mixture containing cement of less than or equal to 50% by weight (dry), and equal to or greater than 50% by weight of graphite, and more preferably a mixture containing between 25-50% by weight (dry) of cement and 50-75% by weight (dry) of graphite, or another electrically conductive material such as granular metal, metal coated particles, coke, graphite, and/or combinations thereof

TABLE I

	Resistivity (ohm cm)					
Sample ID	load lbs 0 lbs	load lbs 50 lbs	load lbs 100 lbs	load lbs 150 lbs	load lbs 200 lbs	load lbs 250 lbs
A	0.11	0.09	0.08	0.07	0.07	0.07
B	0.45	0.19	0.14	0.12	0.10	0.10

[0241] In order to understand the utility of using a strategically placed granular material at the connection point, it is helpful to consider mathematical concepts describing the flow of current through a body. FIG. **12** demonstrates a flow of current through a fracture plane **1200** in a geological formation. Arrows demonstrate current increments in the x and y directions for partial derivative equations. Arrow i_x indicates electrical current flowing in the x direction while arrow i_y indicates electrical current flowing in they direction. Reference "t" indicates the thickness of the fracture **1200** at a point (x, y).

[0242] In fracture plane **1200**, current moves in the x direction from a first point location x to a second location x+dx. The current value changes from i_x+di_x. Similarly, current moves in the y direction from a first point location y to a second point location y+dy. The current value changes from i_y to di_y. If current enters or leaves the fracture at the location (x, y), this source term may be written as Q(x, y) and has units of Amperes/m^2. This represents a source of current at a point in a fracture.

[0243] As current moves charge is conserved. Charge conservation is the principle that electric charge can neither be created nor destroyed; the quantity of electric charge is always conserved. According to the theory of conservation of charge, the total electric charge of an isolated system remains constant regardless of changes within the system itself. Conservation of charge may be expressed mathematically using partial derivative equations:

$$\frac{\partial(ti_x)}{\partial x} + \frac{\partial(ti_y)}{\partial y} = Q(x, y)$$

wherein:

[0244] i_x=current in the x direction within the reservoir

[0245] i_y=current in the y direction within the reservoir

[0246] t=thickness of a section of a reservoir

[0247] Q(x, y)=source of current at a point in a fracture

[0248] By Ohm's law:

$$i_x = \frac{-1}{p}\frac{\partial V}{\partial x};\ i_y = \frac{-1}{p}\frac{\partial V}{\partial y}$$

wherein:

[0249] ρ=resistivity of material in a reservoir

[0250] V=voltage of material

[0251] As noted, high heat generation may take place at the point connections between the metal conductors and the conductive granular material. A mathematical process has been developed for estimating the heat generation distribution for a fracture having resistive heat. This, in turn, allows for modeling of alternate methods for reducing heat generation at the downhole connection points.

[0252] A first step in this mathematical process is to provide a mapping of the product of conductivity and thickness. This may be expressed as:

$$\frac{t}{\rho} = \text{conductivity} \times \text{thickness}$$

As will be graphically demonstrated below, this first mapping step is conducted across the plane of the fracture.

[0253] A next step in the process is to provide a mapping of the input and output current. These currents may be represented as:

Q(x,y)

As will be graphically demonstrated below, this second mapping step is again conducted across the plane of the fracture.

[0254] The two mapping steps provide input maps. After the maps are created, an equation governing voltage can be solved based upon a voltage distribution in the fracture. An equation governing voltage may be expressed:

$$\frac{\partial}{\partial x}\left(\frac{t}{\rho}\frac{\partial V}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{t}{\rho}\frac{\partial V}{\partial y}\right) = -Q(x, y)$$

[0255] Once the voltage distribution has been calculated, a heating distribution in the fracture can be calculated. This is done from a heat generation equation, as follows:

$$h(x, y) = -t\left(i_x\frac{\partial V}{\partial x} + i_x\frac{\partial V}{\partial y}\right)$$

[0256] Using the mathematical process described above, three different examples or "calculation scenarios" are provided herein to consider the problem of high current density around the power connections. The calculation scenarios involve an approximately 90 foot by 60 foot fracture filled with calcined coke as the granular conductant. The fracture is 0.035 inches thick at its center, with its thickness decreasing toward its periphery. Connections to the granular material within the fracture are made with steel plates. The current into and out of the fracture is introduced through these plates.

[0257] Various figures are provided in connection with the three calculation scenarios. In some instances the figures include a legend which provides the resistivities of the materials used in the three calculations. In the legends, ρ_{coke} refers to the resistivity of the bulk proppant material used in all three scenarios; $\rho_{connector}$ refers to the resistivity of the more conductive material used around the connections in the second scenario; and ρ_{steel}, refers to the resistivity of the steel plates. Of course, this is merely illustrative as the plates could be fabricated from conductive materials other than steel.

Simulation No. 1

[0258] As noted, a solution to the problem of high current density leading to hot spots in the formation is implemented by placing a first type of granular material in the immediate vicinity of the connection between the conductors and the conductive granular material. To demonstrate the efficacy of this approach, a first simulation was conducted in which there was no intermediate material, meaning that the conductive granular material was homogeneous. Direct contact is provided between the steel plates and the homogeneous conductive material.

[0259] The results of the first simulation are demonstrated in FIGS. **13** through **17**. First, FIG. **13** provides a thickness-conductivity map **1300** showing a plan view of a simulated fracture. The fracture is shown at **1310**. The fracture **1310** is filled with a conductive proppant. In this simulation, coke is used as the conductive proppant. The coke has a resistivity (indicated at ρ_{coke}) of 0.001 ohm-m.

[0260] Two steel plates are shown at **1320** within the fracture **1310**. These represent a left plate **1320**L and a right plate **1320**R. The plates **1320** are modeled as four foot long plates that are three inches wide by ½-inch thick. The coke surrounds and immediately contacts each of the steel plates **1320**. The steel plates **1320** serve to deliver current in the fracture **1310** and through the coke. The resistivity of the plates **1320** (indicated at ρ_{steel}), is 0.0000005 ohm-m.

[0261] The map **1300** is gray-scaled to show the value of conductivity of the granular proppant multiplied by its thickness across the map **1300**. This means that the product of conductivity and thickness (t/ρ) for the fracture **1310** is mapped across a plan view of the fracture **1320**. The values are measured in amps/volt. The scale starts at 0-2,000 amps/volt, and goes to 30,000-32,000 amps/volt. At this scale, the proppant in the fracture **1310** entirely falls within the 0-2,000 amps/volt range. Stated another way, the thickness-conductivity product is consistent between 0 and 2,000 amps/volt.

[0262] The plates **1320** are highly conductive. Therefore, the thickness-conductivity of the plates **1320** shows in the 30,000-32,000 amps/volt range.

[0263] FIG. **14** is another view of the thickness-conductivity map **1300** of FIG. **13**. The map **1300** is gray-scaled in finer increments of conductivity multiplied by thickness to distinguish variations in proppant conductivity-thickness within the fracture **1310**. The scale starts at 0.000-0.075 amps/volt, and goes to 1.125-1.200 amps/volt. At this scale, variations in the thickness-conductivity product within the fracture **1310** become evident. At an outer ring, the thickness-conductivity product is within the smallest range of the scale—0.000-0.075 amps/volt. As one moves inward towards the center of the fracture **1310**, concentric bands of increasing thickness-conductivity product are seen. At the center, the thickness-conductivity value is about 0.825 to 0.900 amps/volt.

[0264] It is noted that the conductivity of the coke within the fracture **1310** is constant. Therefore, the demonstrated variations are attributed to fracture thickness variations. The fracture **1310** is thin at the outer edge, and becomes increasingly thick towards its center. This tends to simulate actual fracture geometry.

[0265] The two steel plates **1320** are also seen in FIG. **14**. As noted in connection with FIG. **13**, the thickness-conductivity product of the plates **1320** falls in the 30,000-32,000 amps/volt range. Therefore, the plates **1320** are off of the chart in FIG. **13** and simply show up as being white.

[0266] Next, FIG. **15** provides a current source map **1300**. In this instance, the map **1300** shows movement of current into and out of the fracture **1310**. More specifically, FIG. **15** shows the input and output current for the first simulation. As indicated, the total current into and out of the fracture **1310** is one ampere. In one aspect, current goes into the plate **1320**L on the left, and leaves through the plate **1320**R on the right.

[0267] FIG. **15** includes a scale for current, in units of amps/ft^2. The scale runs from −1.20-−1.05 to 1.05-1.20. In between, the scale moves through −0.15-0.00 and 0.00-0.15. It can be seen that the current entering and leaving the fracture **1310** is 0.0 amps/ft^2 except at the two steel plates **1320**.

[0268] FIG. **16** demonstrates a calculated voltage distribution in the fracture **1310** from the one ampere of total current. Lines with arrows are provided to indicate the electrical current flow, which follows the local voltage gradient. As indicated, the total resistance of the fracture **1310** between the two pieces of steel **1320** is 2.71 Ohms.

[0269] A scale is provided in FIG. **16** measured in volts. The scale moves from −1.6-−1.4 to 1.4-1.6. In between, the scale moves through −0.2-0.0 and 0.0-0.2 volts. It can be seen that strongly negative voltage values exist immediately at the right plate **1320**R, and strongly positive voltage values exist immediately at the left plate **1320**L. It can also be seen that there is a higher concentration of current at the steel plates **1320**.

[0270] Finally, FIG. **17** demonstrates the resulting heating distribution in the fracture **1310** from the first simulation. The units of the map **1300** are Watts/ft^2. A gray-scale is provided indicating values from 0 up to 16 Watts/ft2. As can be seen, the heat distribution in the map **1300** shows a total heat input of 1,000 Watts. 60 of the 1,000 Watts (6% of the heat) are generated within one foot of the ends of the plates **1320**L, **1320**R.

[0271] The heat generation in the simulated fracture **1310** declines rapidly away from the steel plates **1320**. This indicates that much energy was lost at the plates **1320** without generating sufficient heat to pyrolyze solid formation hydrocarbons that would otherwise reside in the formation. Six percent of the heat was generated in just 0.14% of the fracture area **1310**. As a result, excessive heating was demonstrated to occur in the immediate vicinity of the steel plates **1320**. Therefore, a modification is desired to disperse heat away from the plates **1320**.

Simulation No. 2

[0272] A second simulation was conducted wherein an "intermediate material" was placed between the steel plates and the surrounding calcined coke. The intermediate material was a highly conductive material that was placed around the conductive connections. The "intermediate material" was simulated to have an electrical conductivity 100 times that of the calcined coke, or a resistivity of 0.00001 Ohm-Meters. As will be shown, this eliminated the high voltage drop across the area of high current density around the connection points, effectively eliminating the excessive heating around the connection points.

[0273] The results of the second simulation are demonstrated in FIGS. **18** through **23**. First, FIG. **18** provides a thickness-conductivity map **1800** showing a plan view of a simulated fracture. The fracture is shown at **1810**. The fracture **1810** is again filled with a conductive proppant. In this simulation, coke is used as a primary conductive proppant. The coke again has a resistivity (indicated at ρ_{coke}) of 0.001 ohm-m.

[0274] Two steel plates are shown at **1820** within the fracture **1810**. These represent a left plate **1820**L and a right plate **1820**R. The coke surrounds each of the steel plates **1820**. The steel plates **1820** serve to deliver current in the fracture **1810** and through the coke.

[0275] In this second simulation the coke does not immediately contact the steel plates **1820**; rather, a connecting granular material is used around the plates **1820**. The resistivity of the connector material (indicated at $\rho_{connector}$) is 0.00001 ohm-m.

[0276] The map **1800** is gray-scaled to show the value of conductivity of the conductive granular proppants **1820** multiplied by its thickness at various locations across the map **1800**. This means that the product of conductivity and thickness (t/ρ) for the fracture **1810** is mapped across a plan view of the fracture **1820**. The values are measured in amps/volt. The scale starts at 0-2,000 amps/volt, and goes to 30,000-32,000 amps/volt. At this scale, the proppants in the fracture **1810** entirely fall within the 0-2,000 amps/volt range. Stated another way, the thickness-conductivity product is consistent between 0 and 2,000 amps/volt.

[0277] The map **1800** of FIG. **18** has been scaled to distinguish between the conductive granular proppant in the fracture **1810**, and the two steel plates **1820** that make up the electrical connection. The legend in FIG. **18** gives the resistivities of the materials used in the second simulation. The ρ_{coke} refers to the resistivity of the bulk proppant material; the $\rho_{connector}$ refers to the resistivity of the highly conductive material used immediately around the plates **1820**L, **1820**R; and, the ρ_{steel}, refers to the resistivity of the steel plates **1820**.

[0278] The plates **1820** are once again modeled as four-foot-long, three-inch-wide, and ½-inch-thick plates. The plates **1820** are highly conductive, with the thickness-conductivity of the plates **1820** showing in the 30,000-32,000 amps/volt range. The plates **1820** show up as being black.

[0279] FIG. 19 is another view of the thickness-conductivity map 1800 of FIG. 18. The map 1800 is gray-scaled in finer increments of conductivity multiplied by thickness to distinguish variations in proppant conductivity-thickness within the fracture 1810. The scale starts at 0.00-2.50 amps/volt, and goes to 37.50-40.00 amps/volt. At this scale, variations in the thickness-conductivity product between the primary coke proppant and the connector proppant become evident. The conductivity-thickness product across most of the fracture 1800 is within the smallest range of the scale—0.00-2.50 amps/volt. However, concentric rings of proppant having a higher conductivity-thickness product are visible around the plates 1820L, 1820R. Immediately adjacent the plates 1820L, 1820R, the conductivity-thickness product is as high as 17.5 to 20.0 amps/volt. The rings dissipate away from the plates 1820L, 1820R to about 7.5 to 10.0 amps/volt before dropping to the lowest range of 0.00 to 2.50 amps/volt within the coke.

[0280] FIG. 20 is another view of the thickness-conductivity map 1800 of FIG. 18. The map 1800 is gray-scaled in still further finer increments of conductivity multiplied by thickness to distinguish variations in proppant conductivity-thickness within the primary proppant. The scale starts at 0.000-0.075 amps/volt, and goes to 1.125-1.200 amps/volt. The conductivity-thickness product across the fracture 1810 is approximately 0.000 to 0.075 at the edge of the fracture 1810, and increases to about 0.675 to 0.750 at the center of the fracture 1810. However, concentric rings of proppant having a higher conductivity-thickness product are again visible. These rings show up white and are off the scale as their conductivity exceeds the highest range of 1.125 to 1.200.

[0281] In FIG. 20 the plates 1820 cannot be distinguished from the intermediate proppant because they are "off the chart" as well, meaning the conductivity-thickness product is high.

[0282] It is noted that the conductivity of the coke within the fracture 1810 is constant. Therefore, the demonstrated variations in conductivity-thickness product seen in FIG. 20 are attributed to fracture thickness variations. The fracture 1810 is thin at the outer edge, and becomes increasingly thick towards its center. This tends to simulate actual fracture geometry.

[0283] Next, FIG. 21 provides a current source map 1800. In this instance, the map 1800 shows movement of current into and out of the fracture 1810. More specifically, FIG. 21 shows the input and output current for the second simulation. As indicated, the total current into and out of the fracture 1810 is one ampere. In one aspect, current goes into the plate 1820L on the left, and leaves through the plate 1820R on the right. The current entering and leaving the fracture 1810 is zero, except at the steel plates 1820R, 1820L.

[0284] FIG. 21 includes a scale for current, in units of amps/ft^2. The scale runs from −1.20-−1.05 to 1.05-1.20. In between, the scale moves through −0.15-0.00 and 0.00-0.15. It can be seen that the current entering and leaving the fracture 1810 is 0.0 amps/ft^2 except at the two steel plates 1820.

[0285] FIG. 22 demonstrates a calculated voltage distribution in the fracture 1810 from the one ampere of total current. Lines with arrows are provided to indicate the electrical current flow, which follows the local voltage gradient. As indicated, the total resistance of the fracture 1810 between the two plates 1820 is 1.09 Ohms, indicating that the higher conductivity material around the plates 1820 has decreased the overall resistance in the fracture relative to the map 1300 of FIG. 16.

[0286] A scale is provided in FIG. 22 measured in volts. The scale moves from −0.64-−0.56 to 0.56-0.64. In between, the scale moves through −0.08-0.0 and 0.0-0.08 volts. These ranges are lower than in the corresponding map 1300 of FIG. 16. This is because total resistance in fracture plane 1810 is lower.

[0287] It can be seen in FIG. 22 that negative voltage values exist immediately at the right plate 1820R, and positive voltage values exist immediately at the left plate 1820L. Of interest, current is still focused in the vicinity of the plates 1820, meaning that there is a higher concentration of current at the steel plates 1820. However, the current pathways can be seen to bend as they enter and leave the higher conductivity areas around the plates 1820.

[0288] Finally, FIG. 23 demonstrates the resulting heating distribution in the fracture 1810 from the simulation. The units of the map 1800 are Watts/ft^2. A gray-scale is provided indicating values from 0.0-0.2 up to 3.0-3.2 Watts/ft^2. As can be seen, the heat distribution in the map 1800 shows a total heat input of 1,000 Watts. However, only 3.3 of the 1,000 Watts (0.33% of the heat) are generated within 1 foot of the ends of the connecting plates 1820L, 1820R. This is a substantial reduction in localized heat generation over the first simulation demonstrated in FIG. 17, proving a more uniform heating of the fracture 1810.

[0289] It is again noted that moderate heat is indicated at the respective ends of the plates 1820L, 1820R. However, these heat areas do not reflect extensive heating within the overall fracture 1810 and provide no cause for concern.

Simulation No. 3

[0290] Next, a third simulation was conducted wherein a non-conductive material was used as the connecting granular material. The non-conductive material was specifically placed at the ends of the simulated steel plates. The non-conductive material operates to redirect current in the formation to mitigate excessive heating around the steel connections. This is another alternative method for eliminating the high heating in the area of high current density around the plates, effectively reducing the excessive heating experienced in the first simulation so that the fracture receives a more uniform heat distribution.

[0291] The results of the third simulation are demonstrated in FIGS. 24 through 28. First, FIG. 24 provides a conductivity map 2400 showing a plan view of a simulated fracture. The fracture is shown at 2410. The fracture 2410 is again filled with a conductive proppant. In this simulation, coke is used as a primary conductive proppant. The resistivity of the coke (indicated at ρ_{coke}) is 0.001 ohm-m.

[0292] Two steel plates are shown at 2420 within the fracture 2410. These represent a left plate 2420L and a right plate 2420R. The coke surrounds each of the steel plates 2420. The steel plates 2420 serve to deliver current in the fracture 2410 and through the coke.

[0293] In this third simulation the coke does not immediately contact all of the steel plates 2420; rather, an intermediate granular material is used around the plates 2420 with coke contacting the plates 2420 only at respective ends. In this instance, the granular material is substantially non-conductive. Thus, the resistivity of the coke is 0.001 ohm-m, while the resistivity of the granular connector material (indicated at $\rho_{connector}$) is essentially infinite.

[0294] The map 2400 is gray-scaled to show the value of conductivity of the conductive granular proppant multiplied by its thickness at various locations across the map **2400**. This means that the product of conductivity and thickness (t/ρ) for the fracture **2410** is mapped across a plan view of the fracture **2420**. The values are measured in amps/volt.

[0295] The map **2400** of FIG. **24** has been scaled to distinguish between the coke in the fracture **2410**, and the two steel plates **2420** that make up the electrical connection. The legend in FIG. **24** gives the resistivities of the materials used in all the third simulation. The ρ_{coke}, refers to the resistivity of the bulk proppant material; the $\rho_{connector}$ refers to the resistivity of the non-conductive granular material used around the connectors **2420**L, **2420**R in the third simulation; and, the ρ_{steel}, refers to the resistivity of the steel plates **2420**. The scale starts at 0-2,000 amps/volt, and goes to 30,000-32,000 amps/volt. At this scale, the resistivity values for the proppant in the fracture **2410** (ρ_{coke}) entirely fall within the 0-2,000 amps/volt range. Stated another way, the thickness-conductivity product is consistent between 0 and 2,000 amps/volt.

[0296] In the third simulation, the plates **2420** are modeled as 27 feet long, 3 inches wide, and ½-inch thick. Compared to the four-foot plates **1820** used in the second simulation, the plates **2420** of the third simulation are very long. This is because the connecting granular material used in the third simulation is substantially non-conductive. The longer plates **2420** provide additional surface area through which current may travel into the fracture **2410**. The plates **1820** are highly conductive, with the thickness-conductivity of the plates **2420** showing in the 30,000-32,000 amps/volt range. The current into and out of the fracture **2410** is introduced through the plates **2420**.

[0297] FIG. **25** is another view of the conductivity map **2400** of FIG. **24**. The map **2400** is gray-scaled in finer increments of conductivity multiplied by thickness to distinguish variations in proppant conductivity-thickness within the fracture **2410**. The scale starts at 0.000-0.075 amps/volt, and goes to 1.125-1.200 amps/volt. The conductivity-thickness product across the fracture **2410** is approximately 0.000 to 0.075 at the edge of the fracture **2410**, and increases to about 0.675 to 0.750 at the center of the fracture **1810**. However, concentric rings of substantially non-conductive proppant appear at ends of the plates **2420**L, **2420**R. These rings show up almost white as their conductivity is zero.

[0298] The map **2400** of FIG. **25** has been scaled to distinguish variations in conductivity-thickness in the coke-filled bulk of the fracture **2410**. The coke proppant is indicated at **2425**. The conductivity of the coke proppant **2425** within the fracture **2410** is constant. Therefore, the demonstrated variations in conductivity-thickness product are attributed to fracture thickness variations. The fracture **2410** is thin at the outer edge, and becomes increasingly thick towards its center. This tends to simulate actual fracture geometry.

[0299] FIG. **25** also shows where non-conductive material (t/ρ=0) has been emplaced around the ends of the steel plates **2420**L, **2420**R. The non-conductive granular material is indicated at **2427**. This non-conductive material **2427** interrupts the flow of current from the plates **2420**L, **2420**R to the bulk proppant **2425**.

[0300] The plates **2420** are also visible in FIG. **25**. The extremely high conductivity plates **2420** show up in FIG. **25** as white lines, indicating an off-scale value.

[0301] Next, FIG. **26** provides a current source map **2400**. In this instance the map **2400** shows movement of current into and out of the fracture **2410**. More specifically, FIG. **26** shows the input and output current for the third simulation. As indicated, the total current into and out of the fracture **2410** is one ampere. In one aspect, current goes into the connector **2420**L on the left, and leaves through the connector **2420**R on the right. The current entering and leaving the fracture **2410** is zero except at the steel plates **2420**R, **2420**L.

[0302] It is noted that the 27-foot length of the respective connectors **2420**L and **2420**R appears abbreviated in the view of FIG. **26**. This is because current is only being supplied near the ends of the plates **2420**. It is noted that the exposed portion in each of plate **2422**L and **2422**R is shorter in FIG. **26** than in FIG. **25**. This is indicative of where the current has been applied.

[0303] FIG. **26** includes a scale for current, in units of amps/ft^2. The scale runs from −1.20-−1.05 to 1.05-1.20. In between, the scale moves through −0.15-0.00 and 0.00-0.15. It can be seen that the current entering and leaving the fracture **2410** is 0.0 amps/ft^2 except at a portion of the two steel plates **2420** that are in contact with the conductive proppant.

[0304] FIG. **27** demonstrates a calculated voltage distribution in the fracture **2410** from the one ampere of total current. Lines with arrows are provided to indicate the electrical current flow, which follows the local voltage gradient. As indicated, the total resistance of the fracture **2410** between the two plates **2420** is 2.39 Ohms. This is slightly less than the 2.71 Ohms prevalent in FIG. **16** from the first simulation. Thus, while the non-conductive connecting material **2427** around the ends of the plates **2420** should increase the resistance relative to the map **1300** of FIG. **16**, the steel plates are much longer, and their impact is to decrease the overall resistance of the fracture **2410**.

[0305] A scale is provided in FIG. **27** measured in volts. The scale moves from −1.28-−1.12 to 1.12-1.28. In between, the scale moves through −0.16-0.0 and 0.0-0.16 volts.

[0306] It can be seen in FIG. **27** that negative voltage values exist immediately at the right connector **2420**R, and positive voltage values exist immediately at the left connector **2420**L. Of interest, current is still focused in the vicinity of the plates **2420**, meaning that there is a higher concentration of current at the steel plates **2420**. However, no current pathways are seen in the areas where the non-conductive intermediate granular material **2427** resides. The current must now go around the non-conductive material **2427**, effectively mitigating the highly focused current of the first simulation.

[0307] Finally, FIG. **28** demonstrates the resulting heating distribution in the fracture **2410** from the simulation. The units of the map **2400** are measured in Watts/ft^2. A gray-scale is provided indicating values from 0.0-0.2 up to 3.0-3.2 Watts/ft^2. As can be seen, the heat distribution in the map **2400** in FIG. **28** shows a total heat input of 1,000 Watts. No areas of intense heat generation around the plates **2420**L, **2420**R are seen. Indeed, heat generation is essentially zero in the area where the non-conductive granular material **2427** is emplaced. However, the heating distribution is not nearly as uniform as the heating distribution seen in FIG. **23** for the second simulation. For this reason, the use of higher conductivity material (as in the second simulation) rather than non-conductive material (as in the third simulation) is considered preferable.

[0308] The above-described processes may be of merit in connection with the recovery of hydrocarbons in the Piceance Basin of Colorado. Some have estimated that in some oil shale deposits of the Western United States, up to 1 million barrels of oil may be recoverable per surface acre. One study has estimated the oil shale resource within the nahcolite-bearing portions of the oil shale formations of the Piceance Basin to be 400 billion barrels of shale oil in place. Overall, up to 1 trillion barrels of shale oil may exist in the Piceance Basin alone.

[0309] Certain features of the present invention are described in terms of a set of numerical upper limits and a set of numerical lower limits. It should be appreciated that ranges formed by any combination of these limits are within the scope of the invention unless otherwise indicated. Although some of the dependent claims have single dependencies in accordance with U.S. practice, each of the features in any of such dependent claims can be combined with each of the features of one or more of the other dependent claims dependent upon the same independent claim or claims.

[0310] While it will be apparent that the invention herein described is well calculated to achieve the benefits and advantages set forth above, it will be appreciated that the invention is susceptible to modification, variation and change without departing from the spirit thereof.

What is claimed is:

1. A method for heating a subsurface formation using electrical resistance heating, comprising:

providing two or more wellbores that penetrate an interval of solid organic-rich rock within the subsurface formation;

establishing at least one fracture in the organic-rich rock from at least one of the two or more wellbores;

providing electrically conductive material in the at least one fracture so as to provide electrical communication between the two or more wellbores, the electrically conductive material comprising (i) first portions placed in contact with each of the two or more wellbores and having a first bulk resistivity, and (ii) a second electrically conductive portion intermediate the two or more wellbores and having a second bulk resistivity; and

passing electric current through the at least one fracture such that resistive heat is generated within the electrically conductive material sufficient to pyrolyze at least a portion of the organic-rich rock into hydrocarbon fluids, wherein the generated heat is lower within the first portions of the electrically conductive material than in the second portion of the electrically conductive material.

2. The method of claim **1**, wherein the organic-rich rock comprises oil shale.

3. The method of claim **2**, wherein:

each of the two or more wellbores is completed substantially vertically; and

the at least one fracture is substantially horizontal.

4. The method of claim **2**, wherein:

each of the two or more wellbores is completed substantially horizontally; and

the at least one fracture is substantially vertical.

5. The method of claim **2**, wherein the electrically conductive material is a granular material that serves as a proppant.

6. The method of claim **2**, wherein the first portions of the electrically conductive material comprise granular metal, metal coated particles, coke, graphite, or combinations thereof.

7. The method of claim **2**, wherein the second portion of the electrically conductive material comprises granular metal, metal coated particles, coke, graphite, or combinations thereof.

8. The method of claim **2**, wherein the resistivity of the material comprising the second portion of the electrically conductive material is about 10 to 100 times greater than the resistivity of the material comprising the first portions of the electrically conductive material.

9. The method of claim **2**, wherein:

the first portions of the electrically conductive material are substantially non-conductive; and

the second portion of the electrically conductive material contacts at least a portion of each of the two or more wellbores.

10. The method of claim **9**, wherein the first portions of the electrically conductive material comprise silica, quartz, cement chips, sandstone, or combinations thereof.

11. The method of claim **2**, wherein the resistivity of the first portions of the electrically conductive material is about 0.005 Ohm-Meters.

12. The method of claim **2**, wherein the resistivity of the first portions of the electrically conductive material is between about 0.00001 Ohm-Meters and 0.00005 Ohm-Meters.

13. The method of claim **2**, wherein the resistivity of the first portions of the electrically conductive material approaches infinity.

14. The method of claim **2**, wherein the at least one fracture is formed hydraulically.

15. The method of claim **2**, further comprising:

continuing to pass electrical current through the first and second portions of electrically conductive material so as to cause pyrolysis of oil shale into hydrocarbon fluids; and

producing hydrocarbon fluids from the subsurface formation to a surface processing facility.

16. A method for heating a subsurface formation using electrical resistance heating, comprising:

creating at least one passage in the subsurface formation between a first wellbore located at least partially within the subsurface formation and a second wellbore also located at least partially within the subsurface formation;

providing an electrically conductive material into the at least one passage to form an electrical connection, the electrical connection providing electrical communication between the first wellbore and the second wellbore;

providing a first electrically conductive member in the first wellbore so that the first electrically conductive member is in electrical communication with the electrical connection;

providing a second electrically conductive member in the second wellbore, so that the second electrically conductive member is in electrical communication with the electrical connection, thereby forming an electrically conductive flow path comprised at least of the first electrically conductive member, the electrical connection and the second electrically conductive member; and

establishing an electrical current through the electrically conductive flow path, thereby generating heat within the electrically conductive flow path due to electrical resistive heating, with at least a portion of the generated heat thermally conducting into the subsurface formation, and wherein the generated heat is comprised of first heat generated in proximity to the first electrically conductive member and the second electrically conductive member, and second heat generated from the electrically conductive granular material intermediate the first electrically conductive member and the second electrically conductive member, with the first heat being less than the second heat.

17. The method of claim **16**, wherein the subsurface formation is an organic-rich rock formation.

18. The method of claim **17**, wherein the subsurface formation contains heavy hydrocarbons.

19. The method of claim **17**, wherein the subsurface formation is an oil shale formation.

20. The method of claim **17**, wherein:

the electrically conductive material is a granular material; and

the electrical connection is a granular electrical connection.

21. The method of claim **20**, wherein the generated heat causes pyrolysis of solid hydrocarbons within at least a portion of the subsurface formation.

22. The method of claim **21**, wherein:

the electrically conductive granular material comprises (i) first portions in immediate proximity to the first electrically conductive member and the second electrically conductive member, respectively, and (ii) a second portion intermediate the first portions around the first and second electrically conductive members; and

a resistivity of the first portions is different than a resistivity of the second portion.

23. The method of claim **22**, wherein the first portions of the electrically conductive granular material have a sufficiently low electrical resistivity so as to provide electrical conduction without substantial heat generation.

24. The method of claim **22**, wherein the first portions of the electrically conductive granular material comprises granular metal, metal coated particles, coke, graphite, or combinations thereof.

25. The method of claim **22**, wherein the second portion of the electrically conductive granular material comprises granular metal, metal coated particles, coke, graphite, or combinations thereof.

26. The method of claim **22**, wherein the resistivity of the material comprising the second portion of the electrically conductive granular material is about 10 to 100 times greater than the resistivity of the material comprising the first portions of the electrically conductive granular material.

27. The method of claim **22**, wherein the first portions of the electrically conductive granular material comprises less than or equal to 50 percent by dry weight of cement and 50 percent or more by dry weight of graphite.

28. The method of claim **22**, wherein the first portions of the electrically conductive granular material comprises between 50 to 75 percent of granular metal, metal coated particles, coke, graphite, or combinations thereof.

29. The method of claim **22**, wherein:

the first portions of the electrically conductive granular material are substantially non-conductive; and

the second portion of the electrically conductive granular material contacts at least a portion of each of the first and second electrically conductive members.

30. The method of claim **29**, wherein the first portions of the electrically conductive granular material comprise silica, quartz, cement chips, sandstone, or combinations thereof.

31. The method of claim **26**, wherein the resistivity of the first portions of the electrically conductive granular material is about 0.005 Ohm-meters.

32. The method of claim **26**, wherein the resistivity of the first portions of the electrically conductive material approaches infinity.

33. The method of claim **22**, wherein:

the first wellbore and the second wellbore is each completed substantially vertically; and

the passage in the subsurface formation comprises a substantially vertically fracture.

34. The method of claim **26**, wherein:

the first wellbore and the second wellbore is each completed substantially horizontally; and

the at least one passage in the subsurface formation comprises a first substantially vertical fracture.

35. The method of claim **33**, further comprising:

providing a third electrically conductive member in a third wellbore, such that the third electrically conductive member is also in electrical communication with the electrical connection and is part of the electrically conductive flow path; wherein

the third wellbore is completed substantially horizontally;

the at least one passage in the subsurface formation comprises a second substantially vertical fracture; and

the second wellbore intersects both the first fracture and the second fracture.

36. The method of claim **22**, wherein the material comprising at least a portion of the first electrically conductive member, the second electrically conductive member, or both has an electrical resistivity of less than 0.0005 Ohm-meters.

37. The method of claim **22**, further comprising:

continuing to pass an electrical current through the electrical connection until the subsurface formation immediately adjacent the electrically conductive flow path reaches a selected temperature; and

reducing an amount of current through the electrical connection.

38. A system for in situ heating of a subsurface formation using electrical resistance heating, comprising:

a plurality of wellbores that penetrate an interval of solid organic-rich rock within the subsurface formation;

at least one fracture in the organic-rich rock established from at least one of the wellbores, wherein the at least one fracture comprises electrically conductive material to provide electrical communication between at least two of the wellbores, the electrically conductive material including

(i) first portions placed in contact with at least two wellbores and having a first bulk resistivity, and

(ii) a second electrically conductive portion intermediate the at least two wellbores and having a second bulk resistivity; and

at least one electrical conductor operatively connected to the first portions of the electrically conductive material in each of the at least two wellbores, the at least one electrical conductor being configured to pass electric current through the at least one fracture such that resistive heat is generated within the electrically conductive material sufficient to pyrolyze at least a portion of the organic-rich rock into hydrocarbon fluids, and wherein the generated heat is lower within the first portions of the electrically conductive material than in the second portion of the electrically conductive material.

39. The system of claim **38**, wherein:

each of the two or more wellbores is completed substantially vertically; and

the at least one fracture is substantially horizontal.

40. The system of claim **38**, wherein:

each of the two or more wellbores is completed substantially horizontally; and

the at least one fracture is substantially vertical.

41. The system of claim **38**, wherein the electrically conductive material is a granular material that serves as a proppant.

42. The system of claim **38**, wherein the first portions of the electrically conductive material comprise granular metal, metal coated particles, coke, graphite, or combinations thereof.

43. The system of claim **38**, wherein the second portion of the electrically conductive material comprises granular metal, metal coated particles, coke, graphite, or combinations thereof.

44. The system of claim **38**, wherein the resistivity of the material comprising the second portion of the electrically conductive material is about 10 to 100 times greater than the resistivity of the material comprising the first portions of the electrically conductive material.

45. The system of claim **38**, wherein:

the first portions of the electrically conductive material are substantially non-conductive; and

the second portion of the electrically conductive material contacts at least a portion of each of the two or more wellbores.

46. The system of claim **45**, wherein the first portions of the electrically conductive material comprise silica, quartz, cement chips, sandstone, or combinations thereof.

47. The system of claim **38**, wherein the resistivity of the first portions of the electrically conductive material is about 0.005 Ohm-Meters.

48. The system of claim **38**, wherein the resistivity of the first portions of the electrically conductive material is between about 0.00001 Ohm-Meters and 0.00005 Ohm-Meters.

49. The system of claim **38**, wherein the resistivity of the first portions of the electrically conductive material approaches infinity.

50. The system of claim **38**, wherein the at least one fracture is formed hydraulically.

51. The system of claim **38**, further comprising at least one production well for producing hydrocarbon fluids from the subsurface formation.

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