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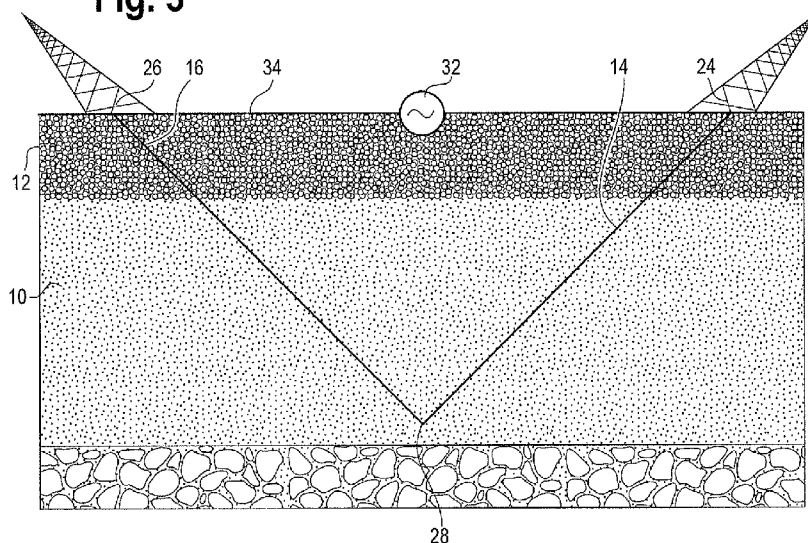
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Fig. 3



(57) Abstract: An array of loop antennas for a heating subsurface formation by emission of RF energy and a method of heating a subsurface formation by an array of subsurface loop antennas is disclosed. The antennas are approximate loops and are positioned in proximity to adjacent loops. The antennas are driven by RF energy.

IN SITU LOOP ANTENNA ARRAYS FOR SUBSURFACE HYDROCARBON HEATING

The invention concerns heating of hydrocarbon materials in geological
5 subsurface formations by radio frequency electromagnetic waves (RF), and more particularly to heating by RF energy emitted from one or more polygonal antennas.

Extraction from heavy oil reservoirs including oil sands deposits, shale
deposits and carbonate deposits, requires heating of the deposits to separate
hydrocarbons from other geologic materials and to maintain hydrocarbons at
10 temperatures at which they will flow. Known methods of heating such deposits include steam heating, electric resistance heating and heating by RF energy.

Heating subsurface heavy oil bearing formations by prior RF systems
has been inefficient due to traditional methods of matching the impedances of the
power source (transmitter) and the heterogeneous material being heated, uneven
15 heating resulting in unacceptable thermal gradients in heated material, inefficient spacing of electrodes/antennae, poor electrical coupling to the heated material, limited penetration of material to be heated by energy emitted by prior antennae and frequency of emissions due to antenna forms and frequencies used. Antennas used for
prior RF heating of heavy oil in subsurface formations have typically been dipole
20 antennas. U.S. Patents nos. 4,140,179 and 4,508,168 disclose prior dipole antennas positioned within subsurface heavy oil deposits to heat those deposits.

Arrays of dipole antennas have been used to heat subsurface
formations. U.S. patent no. 4,196,329 discloses an array of dipole antennas that are
driven out of phase to heat a subsurface formation.

25 An aspect of the invention concerns an array of loop antennas for a heating subsurface formation comprising a first loop antenna that is positioned within a subsurface formation, lies approximately within a first plane and generally forms an arc of radius r , and a second loop antenna positioned within the subsurface formation adjacent to the first antenna and generally forming a second arc of radius r and lying
30 approximately within a second plane that is parallel to the first plane and separated from the first plane by the distance r .

Another aspect of the invention concerns a method of heating a subsurface formation comprising positioning within the subsurface formation a first loop antenna that lies generally along a first arc of radius r and is generally within a first plane, positioning within the subsurface formation a second loop antenna that lies
5 generally along a second arc of radius r and is generally within a second plane that is approximately parallel to and separated from the first plane by the distance r , and providing RF energy of equal frequency, amplitude and phase to the first and second antennas.

Another aspect of the invention concerns a loop antenna approximating
10 a helix to form an array of loop antennas for heating a subsurface formation. The antenna forms a first loop that is positioned within the subsurface formation, lies approximately within a first plane and is formed by a first plurality of connected segments of the antenna that extend from a first location to a second location. The antenna also forms a second loop that is positioned within the subsurface formation,
15 that lies approximately within a second plane, is separated from the first loop and is formed by a second plurality of connected segments of the antenna extending from a third location to a fourth location. A segment of the antenna extends from the second location to the third location.

FIG. 1 is an illustration of simulated heating of a subsurface formation
20 by a dipole antenna.

FIG. 2 is an illustration of simulated heating of a subsurface formation by a loop antenna.

FIG. 3 illustrates heating of an oil sands formation by an polygonal loop antenna according to the present invention.

25 FIG. 4 illustrates formation of linked boreholes forming a four sided polygon to accept a loop antenna according to the present invention..

FIG. 5 illustrates an antenna according to the present invention in the boreholes illustrated by Fig. 4.

FIG. 6 is an isometric view of an array of subsurface polygonal loop
30 antennas according to the present invention.

FIG. 7 illustrates the magnetic near field created by the array of polygonal loop antennas shown by Fig. 6.

FIG. 8 is an isometric view of a subsurface antenna according to the present invention that approximates a helix by a series of partial loops.

5 FIG. 9 illustrates a cross section of an antenna according to the present invention formed by Litz conductors.

The present invention will now be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. This invention may, however, be embodied in many different forms and
10 should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are examples of the invention, which has the full scope indicated by the language of the claims. Like numbers refer to like elements throughout.

Subsurface formations are heated by RF emission from antennas that are positioned within and therefore are surrounded by the material to be heated.
15 Subsurface material is heated primarily in the reactive near field region of embedded antennas. Heating of subsurface material by dipole antennas is therefore primarily effected by dielectric heating by near field electric (E) field. As illustrated by Fig. 1, heating of homogeneous material adjacent to a dipole antenna, as evaluated by specific absorption rate, varies significantly along the length of the antenna. Intense
20 heating of material near an antenna is undesirable because intense heating of small areas is not an efficient use of energy and is also undesirable because overheating of subsurface formations can create material that is impermeable and prevent or impede extraction of hydrocarbon material.

RF fields emitted by loop antennas differ from the fields emitted by
25 dipole antennas in the near field region. The curl of a loop antenna creates near field magnetic fields. A loop antenna may be approximated by a polygon. The greater the number of sides of the polygon, the closer the approximation of the curl of a curved loop antenna. As shown by Fig. 2, the near field created by a loop antenna heats homogeneous material that surrounds the antenna much more uniformly than do

dipole antennas. Loop antennas are particularly advantageous for heating materials in which eddy currents are created by magnetic fields. Water is one such material.

Hydrocarbons that must be heated to be extracted from subsurface formations, including oil sands deposits, shale deposits and carbonate deposits, are generally mixed with other materials including water. There other materials make heating by RF emissions feasible as hydrocarbons are generally heated poorly by RF emissions. Applying RF emissions to subsurface hydrocarbon formations generally heats material other than the hydrocarbons and these heated materials heat the hydrocarbons by heat conduction. Hydrocarbons deposits, particularly oil sands deposits typically contain water. Water is conductive and therefore susceptible to heating by magnetic fields. Loop antennas are therefore desirable for heating these deposits within the antenna near field.

Heating of subsurface formations by RF magnetic fields can be increased by injection of an RF susceptor. Sodium hydroxide lye increases the conductivity of the in situ water and thereby increases the flow of eddy electrical currents that are induced by RF magnetic fields.

Figure 3 illustrates heating of an oil sands deposit by a loop antenna according to the present invention. As shown by Fig. 3, an oil sands formation 10 is beneath a covering overburden region 12. Two boreholes, 14 and 16 are drilled from separated locations 24 and 26 on the surface of the overburden 12. The boreholes 14 and 16 extend from the locations 24 and 26, respectively, toward each other to meet at location 28 within the oil sands formation 10. A loop antenna 34 extends from an RF transmitter 32 on the surface of overburden 12. The loop antenna 34 extends from the transmitter 32 to the openings of the boreholes 14 and 16 at locations 24 and 26 on the surface of the overburden 12, and through the boreholes 14 and 16. The loop antenna 34 is only partially positioned within the oil sands formation 10.

Figure 4 illustrates four boreholes, 42, 44, 46 and 48, that are drilled into the oil sands formation 10. The boreholes 42 and 48 are drilled from separated locations 52 and 58, respectively, on the surface of the overburden 12. The boreholes 42 and 48 extend from the locations 52 and 58, respectively, toward each other to

meet at location 62 within the oil sands formation 10. The boreholes 44 and 46 are drilled from separated locations 54 and 56, respectively, on the surface of the overburden 12. The boreholes 44 and 46 extend from locations 54 and 56, respectively, on the surface of overburden 12. Locations 54 and 56 are on a line
5 extending from location 52 to location 58 and are between locations 52 and 58. Location 54 is adjacent to and separated from location 52 and location 56 is adjacent to and separated from location 58. The borehole 44 extends from location 54 generally parallel to borehole 42 to intersect borehole 48 at location 64 which is within the oil sands formation 10 between location 62 and location 58. The borehole
10 46 extends from location 56 generally parallel to borehole 48 to intersect borehole 42 at location 66 which is within the oil sands formation 10 between location 62 and location 52. As shown by Fig. 4, the boreholes 44 and 46 intersect each other at location 68 which is near the interface of the overburden 12 and the oil sands formation 10. The borehole 46 extends from the location 68 to the location 66 and the
15 borehole 44 extends from the location 68 to the location 64. The sections of boreholes 42, 48, 44 and 46 extending from location 66 to 62, location 62 to location 64, location 64 to location 68 and location 68 to location 66, respectively, form four connected borehole segments that form a four side polygon 72 within the oil sands formation 10. The polygon 72 lies generally within a plane.

20 Figure 5 schematically illustrates an antenna 74 extending to the four sided polygon 72 through the borehole 46. The antenna 74 forms a loop within the borehole polygon 72. A transmitter 76, shown at location 56, is connected to antenna 74 to provide an RF signal to the antenna 74.

25 Figure 6 illustrates two antennas, 82 and 92, arranged in an array within an oil sands formation 10. The antennas 82 and 92 each form a four sided polygon loop, 86 and 96 respectively, that lie generally parallel to each other within the oil sands formation 10. The loops 86 and 96, shown in an isometric view by fig. 6, are preferably formed to approximate a loop at a distance r from a center of the polygon. The polygon loops 86 and 96 are not uniformly at the distance r from the
30 center. They may nevertheless be generally characterized by the distance r that

approximates the radius of a loop along which the polygons 86 and 96 lie. As shown by Figure 6, the antennas 82 and 92 are separated by that distance r . The transmitters 84 and 94 drive the antennas 82 and 92, respectively, each providing RF energy to their attached antennas at equal frequency, amplitude and phase.

5 By positioning the antennas 82 and 92 in the positions with respect to each other as illustrated by Figure 6, the near magnetic fields created by the antennas overlap each other to create a zone of approximately constant heating. Figure 7 illustrates the magnetic fields created by the antennas 82 and 92 in the plane 7 as indicated in Figure 6. Cross sections of antennas 82 and 92 are shown on Figure 7.

10 Contours 102, 104, 106, 108 and 110 are at the edges of regions of uniform heating due to near fields of antennas 82 and 92. The near fields created by antennas 82 and 92 in the relative positions shown by Figures 6 and 7 overlap each other to create the illustrated large heated region of material surrounding the antennas 82 and 92.

Fig. 8 shows an antenna 110 positioned within an oil sands formation

15 10. RF energy is provided to the antenna 110 by a transmitter 120. The antenna 110 approximates a helical configuration in the oil sands formation 10 by extending through sections of intersecting boreholes. A borehole 132 extends through the overburden 12 from location 152 on the surface of the overburden 12 and into the oil sands formation 10 to a location 133. A borehole 134 extends into the overburden 12

20 and oil sands formation 10 from a location 154 on the surface of the overburden 12 that is separated from the location 152. The borehole 134 extends to intersect the borehole 132 at location 133 and extends beyond location 133 into the oil sands formation 10 to a location 135. A borehole 136 extends into the overburden 12 and oil sands formation 10 from a location 156 on the surface of the overburden 12 that is

25 separated from the location 152. The borehole 136 extends generally parallel to the borehole 132 to intersect the borehole 134 at location 135. The boreholes 132, 134 and 136 lie in a first plane. A borehole 138 extends into the overburden 12 and oil sands formation 10 from a location 158 on the surface of the overburden 12 that is separated from the locations 152, 154 and 156. The borehole 138 extends to intersect

30 the borehole 136 at a location 137 that is within the oil sands formation 10 and that is

between the locations 135 and 156. The borehole 138 extends from the first plane in which the boreholes 132, 134 and 136 lie.

A borehole 140 extends into the overburden 12 and oil sands formation 10 from a location 160 on the surface of the overburden 12 that is separated from the location 152. The borehole 140 extends generally parallel to borehole 132 to intersect the borehole 138 at a location 139 that is within the oil sands formation 10. The borehole 140 extends beyond the location 139 to a location 141 that is deeper in the oil sands formation 10. A borehole 142 extends into the overburden 12 and oil sands formation 10 from a location 162 on the surface of the overburden 12 that is separated from the location 154. The borehole 142 extends generally parallel to borehole 134 to intersect the borehole 140 at the location 141. The borehole 142 extends beyond the location 141 to a location 143 that is deeper in the oil sands formation 10. A borehole 144 extends into the overburden 12 and oil sands formation 10 from a location 164 on the surface of the overburden 12 that is separated from the locations 160 and 156. The borehole 144 extends generally parallel to borehole 140 to intersect the borehole 142 at the location 143. The boreholes 140, 142 and 144 lie in a second plane. A borehole 146 extends into the overburden 12 and oil sands formation 10 from a location 168 on the surface of the overburden 12 that is separated from the locations 160, 162 and 164. The borehole 146 is generally parallel to the borehole 138 and extends to intersect the borehole 144 at a location 145 that is within the oil sands formation 10 and is between the locations 143 and 164. The borehole 146 extends from the second plane in which the boreholes 140, 142 and 144 lie. A borehole 148 extends into the overburden 12 and the oil sands formation 10 from a location 172 on the surface of the overburden 12 that is separated from the location 162. The borehole 148 intersects the borehole 146 at a location 147 that is within the oil sands formation 10 and between the location 145 and the location 168.

The antenna 110 approximates a helix by a series of connected segments that extend within the intersecting boreholes. A first segment of the antenna 110 extends into the oil sands formation 10 through the borehole 132 to the location 133. A second segment extends from the location 133 through the borehole 134 to the

location 135. A third segment of the antenna 110 extends from the location 135 through the borehole 136 to the location 137. A fourth segment extends from the location 137 through the borehole 138 to the location 139. A fifth segment of the antenna 110 extends from the location 139 through the borehole 140 to the location 141. A sixth segment extends from the location 141 through the borehole 142 to the location 143. A seventh segment of the antenna 110 extends from the location 143 through the borehole 144 to the location 145. An eighth segment of the antenna 110 extends from the location 145 through the borehole 146 to the location 147. A ninth segment of the antenna 110 extends from the location 147 to the surface of the overburden 12 through borehole 148.

The antenna 110 forms an array of partial loop antennas, each partial loop formed by three connected segments extending through boreholes. Partial loops are formed by borehole 132, 134 and 136, boreholes 134, 136 and 138, boreholes 136, 138 and 140, boreholes 138, 140 and 142, boreholes 140, 142 and 144 and boreholes 142, 144 and 146. The partial loop formed by the first, second and third segments in boreholes 132, 134 and 136 lies in the first plane and the partial loop formed by the fifth, sixth and seventh segments in boreholes 140, 142 and 144 lies in the second plane. The series of partial loops formed by the segments of antenna 110 in boreholes 132, 134, 136, 138, 140, 142, 144 and 146 approximate a helix through the oil sands formation 10.

Antennas according to the present invention emit RF energy to heat surrounding subsurface material in the near field region of the antenna. As described by the inventor's U.S. patent no. 7,205,947, the entirety of which is incorporated herein by reference, RF current tends to flow along the surface of conductors in an effect that is referred to as a skin effect. This effect limits the useful amount of a conductors cross section for carrying RF energy. Because antennas according to the present invention are intended to emit significant energy, this skin effect is particularly undesirable in antennas according to the present invention. As described by the applicant's U.S. patent, Litz wires can be used to reduce the undesirable skin effect in an antenna. As shown by the cross section of a Litz wire 122 illustrated by

Fig. 8, a Litz wire is formed by a plurality of wires 130 that are braided together. The plurality of wires 130 are preferably individually insulated wires with an outer insulation 132 to form an insulated bundle 133. Dielectric strands may be included with the plurality of wires 130. Groups 135 of insulated bundles 133 may be braided or twisted together and include an outer insulation 134. The groups 135 may also be braided or twisted together to define the Litz wire antenna loop with a further outer insulation 136. The groups 135 may be braided or twisted about a core 138 made of dielectric.

CLAIMS

1. An array of loop antennas for heating a subsurface formation comprising:
 - 5 a first loop antenna positioned within the subsurface formation, the first antenna lying approximately within a first plane and formed generally along a first arc of radius r ; and
 - a second loop antenna positioned within the subsurface formation, the second antenna
 - 10 adjacent to the first antenna, formed generally along a second arc of radius r ; and lying approximately within a second plane, the second plane being generally parallel to the first plane and separated from the first plane by the distance r .
- 15 2. A method of heating a subsurface formation comprising:
 - positioning a first loop antenna within the subsurface formation to lie generally within a first plane, the first loop antenna lying generally along a first arc of radius r
 - 20 positioning a second loop antenna within the subsurface formation to lie generally within a second plane, the second plane generally parallel to and separated from the first plane by the distance r and the second loop antenna lying generally along a second arc of radius r , and
 - providing RF energy of equal frequency, amplitude and phase to the
 - 25 first and second antennas.
3. A loop antenna approximating a helix to form an array of loop antennas for heating subsurface formation, the antenna comprising:

a first loop positioned within the subsurface formation, the first loop formed by a first plurality of connected segments extending from a first location to a second location;

5 a second loop positioned within the subsurface formation, the second loop
separated from the first loop and formed by a second plurality of connected segments extending from a third location to a fourth location; and
a segment of the second loop extending from the second location
10 to the third location.

4. The invention of any preceding claim wherein the first loop and the second loop are each formed by a series of connected generally straight segments.

15 5. The invention of any preceding claim wherein the first loop and the second loop form a polygon.

6. The invention of any preceding claim wherein the first loop and the second loop each form a four side polygon.

20 7. The invention of any preceding claim wherein the first loop and the second loop are each formed by Litz wire.

8. The invention of any preceding claim further comprising introducing a
25 susceptor into the formation that increases the conductivity of material in the formation.

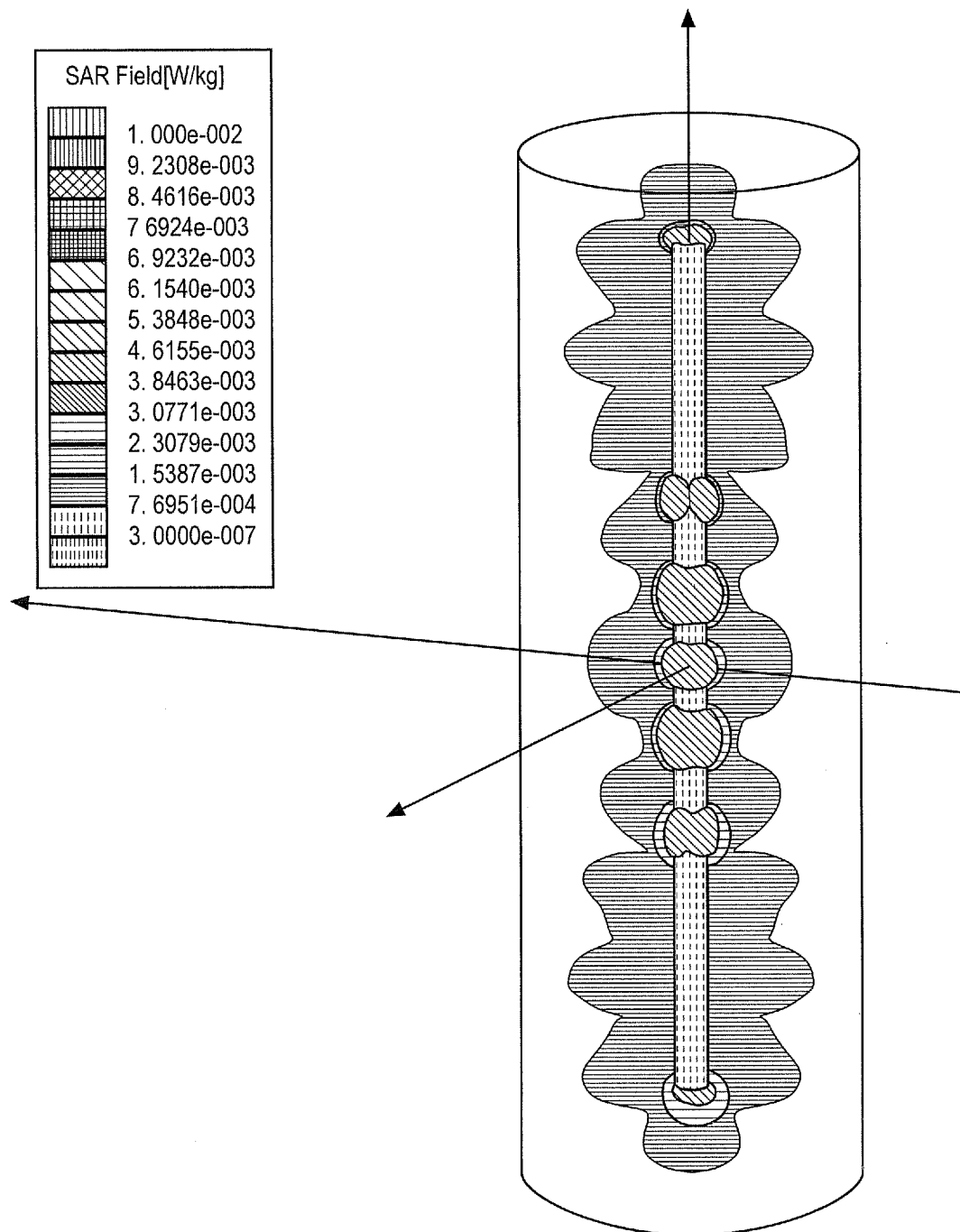
9. The invention of claim 7 wherein the susceptor includes sodium
hydroxide.

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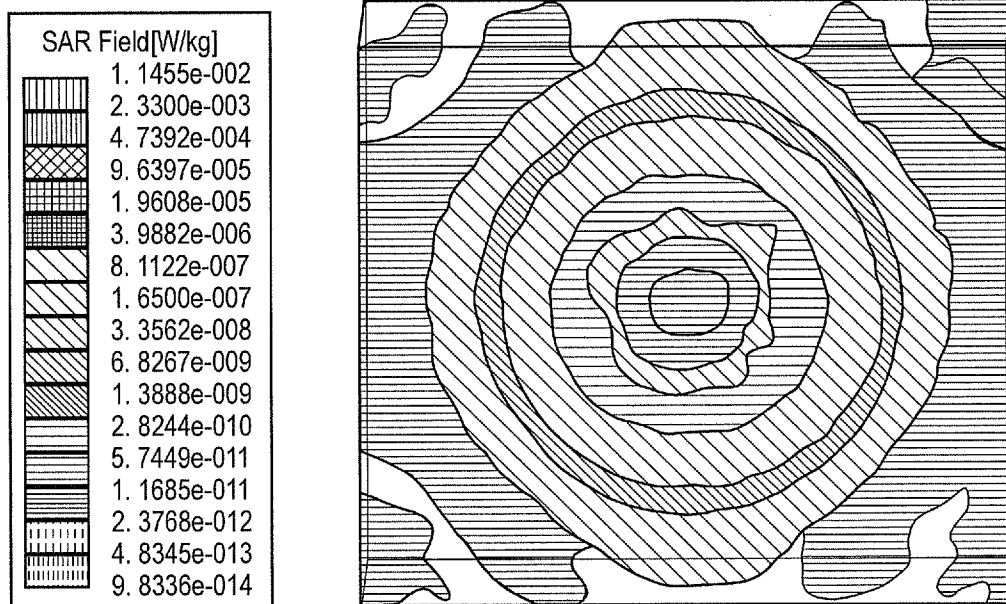
10. The invention of any preceding claim wherein the first loop generally lies in a first plane and the second loop generally lies in a second plane, the second plane being separated from the first plane.

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Fig. 1



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Fig. 2

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Fig. 3

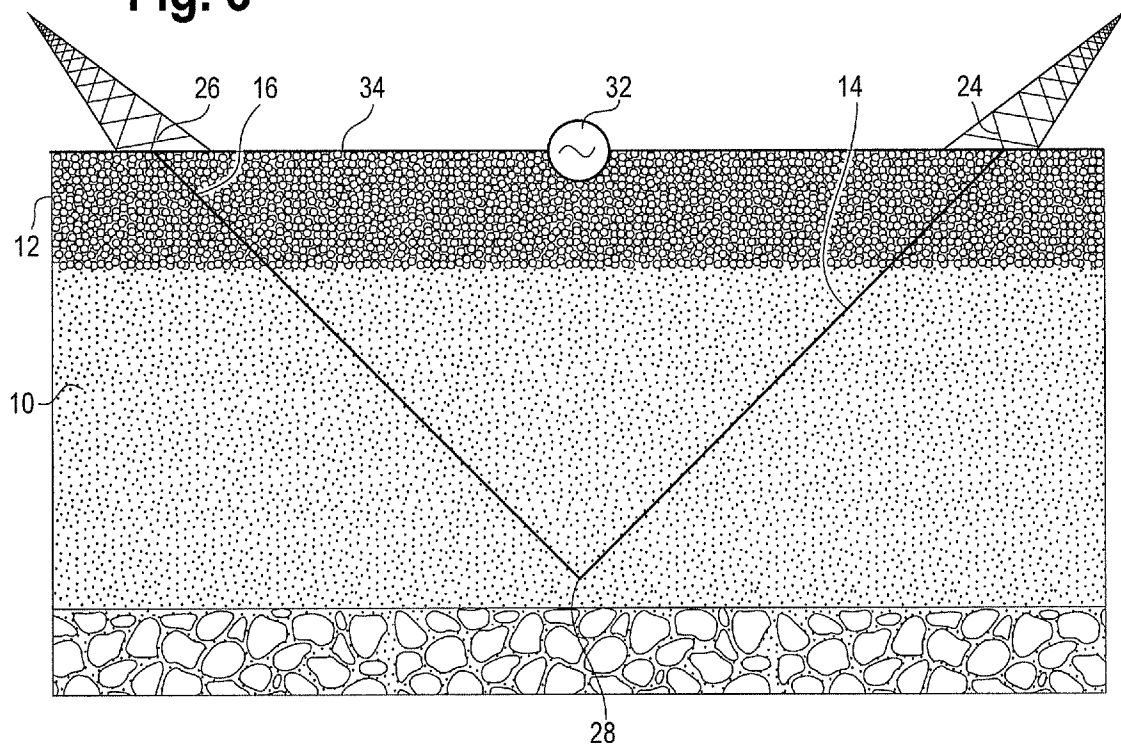
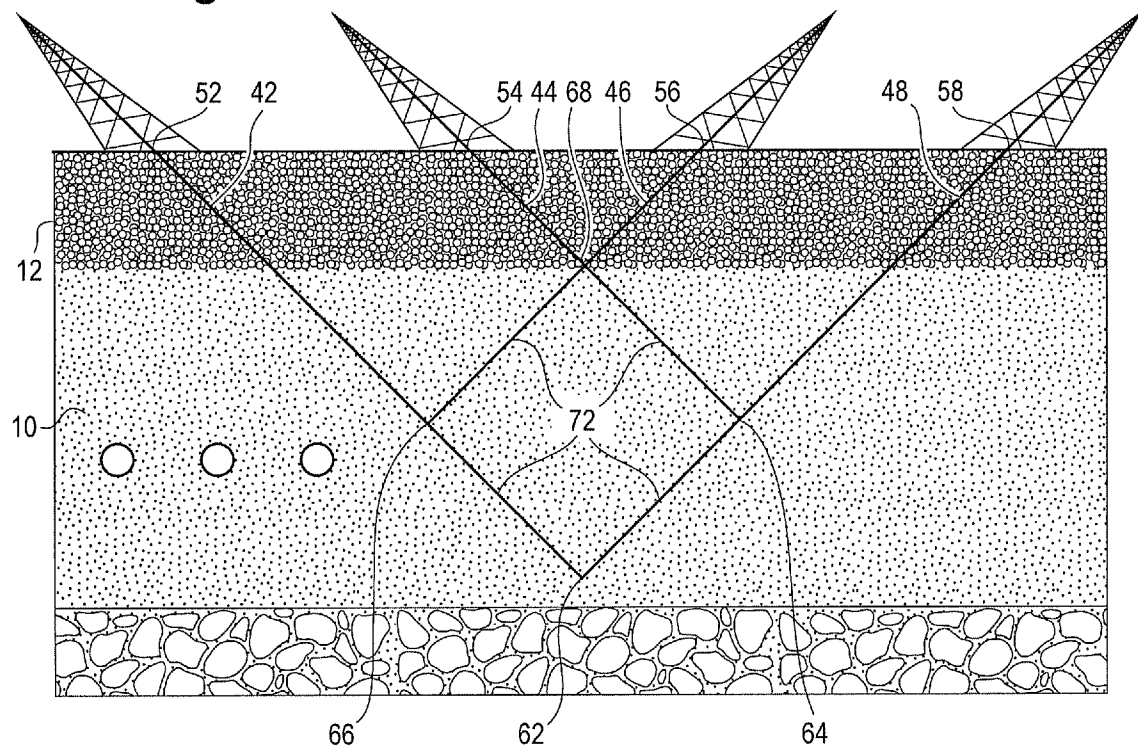


Fig. 4



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Fig. 5

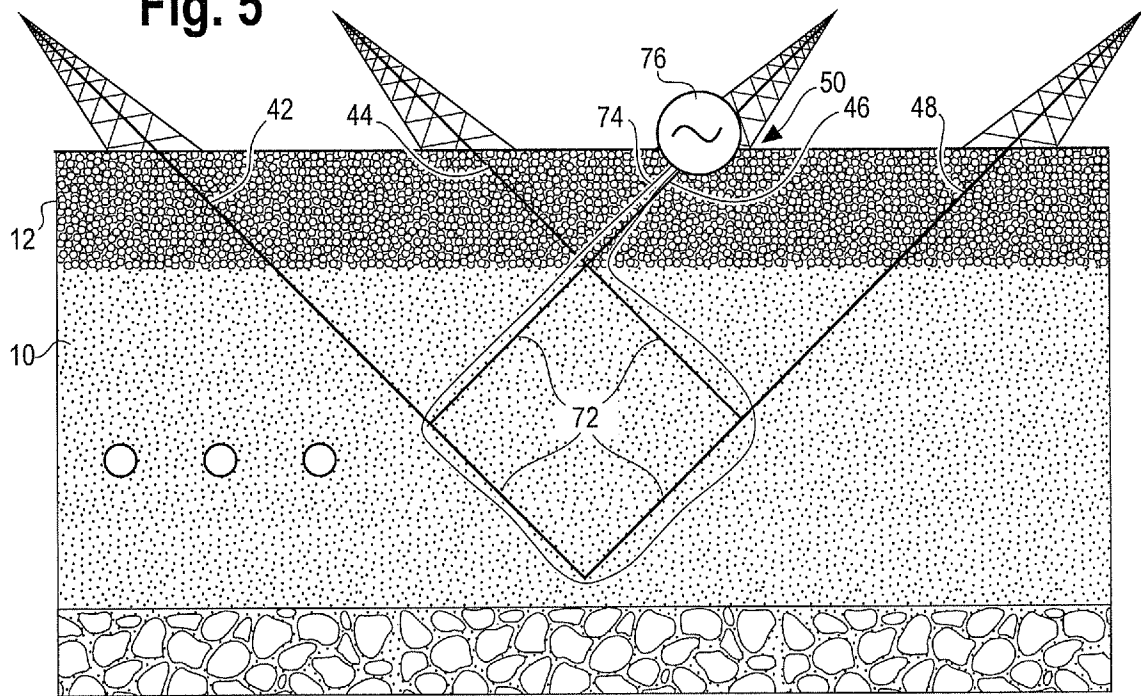
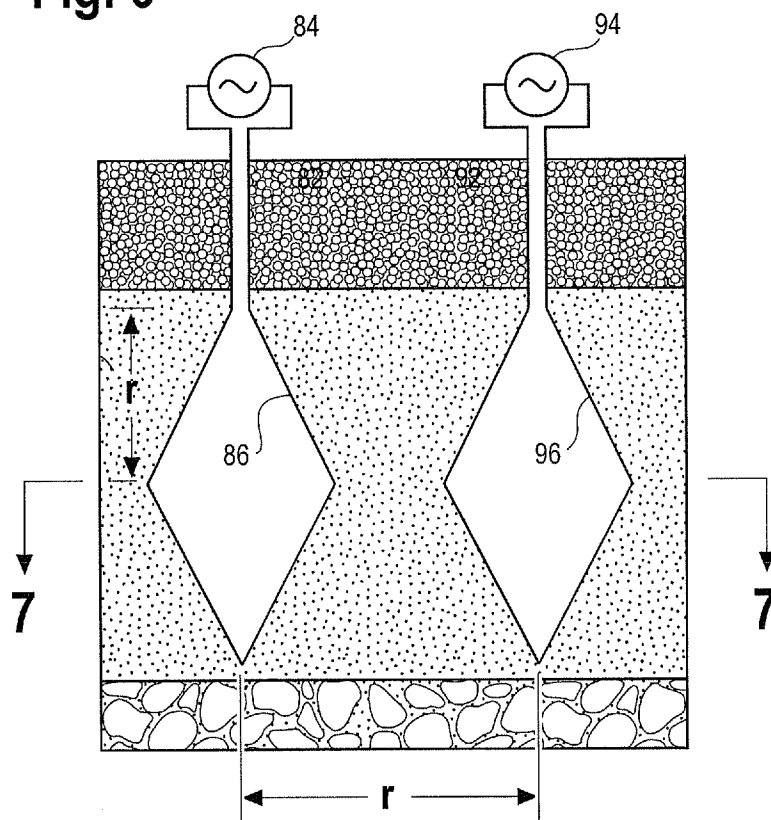
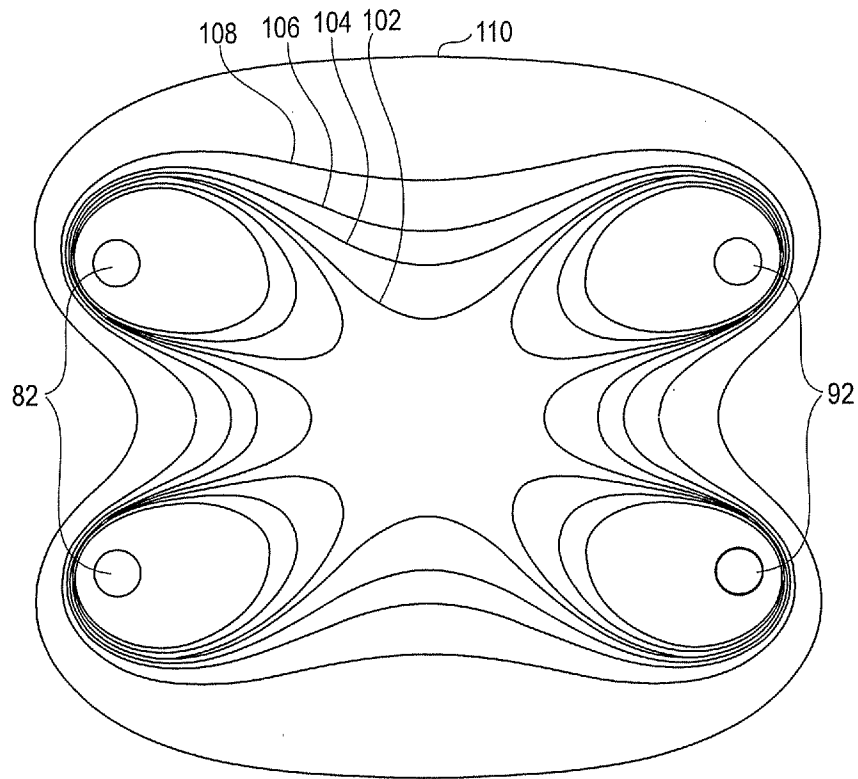


Fig. 6



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Fig. 7



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Fig. 8

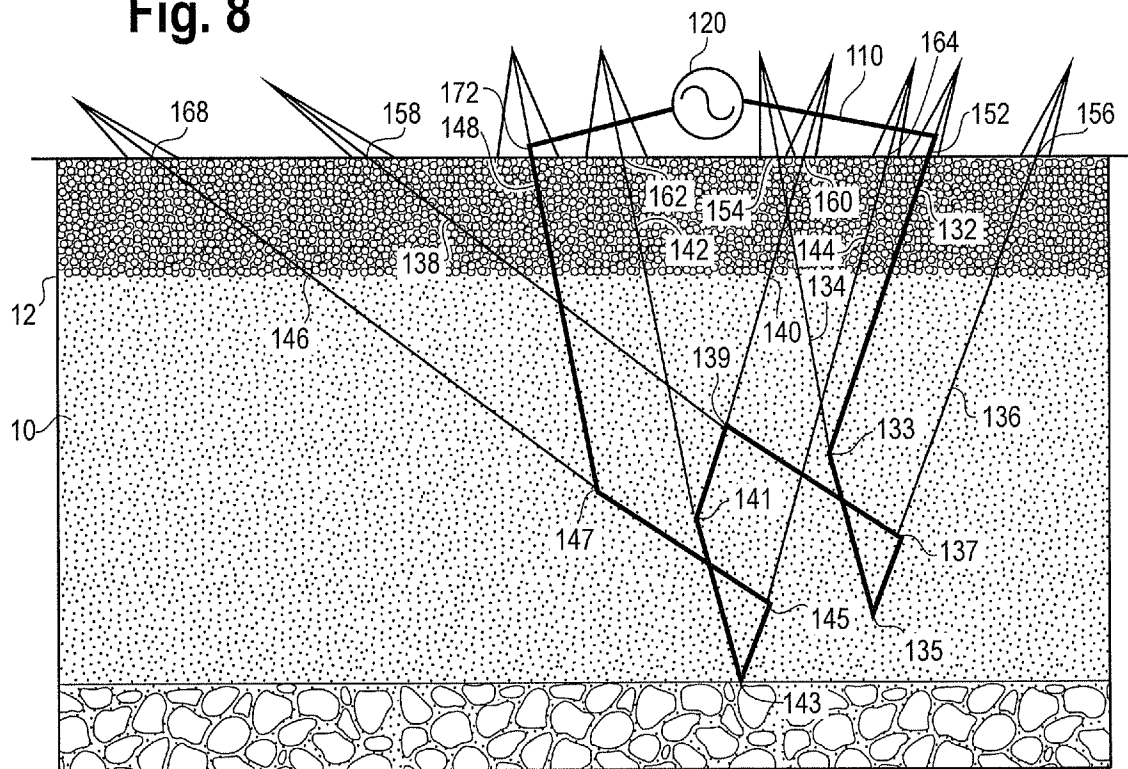


Fig. 9

