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(71) Applicant (for all designated States except US): **BHOM LLC** [US/US]; P.O. Box 278, 56 Crown Drive, Big Horn, WY 82833 (US).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **PAO, Hsueh-Yuan** [US/US]; 978 Redmond Avenue, San Jose, CA 95120 (US).

(74) Agent: **CLEVELAND, Dan**; Lathrop & Gage LC, 4845 Pearl East Circle, Suite 300, Boulder, CO 80301 (US).

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(54) Title: SYSTEM AND METHOD FOR EXTRACTION OF HYDROCARBONS BY IN-SITU RADIO FREQUENCY HEATING OF CARBON BEARING GEOLOGICAL FORMATIONS

(57) Abstract: A method of producing liquid hydrocarbons from a hydrocarbon-bearing rock in situ in a geological formation begins with exploring the formation by drilling a plurality of boreholes into the formation and taking core samples of the hydrocarbon-bearing rock and at least one overburden layer. Electrical parameters of the hydrocarbon-bearing rock and the overburden layer are determined, as well as a roughness of a boundary between the hydrocarbon-bearing rock and the at least one overburden layer. These electrical parameters are used to construct a computer model of a portion of the hydrocarbon-bearing rock and at least one overburden layer, the computer model based upon modeling the formation as a rough-walled waveguide. This computer model is used to simulate propagation of radio frequency energy within the hydrocarbon-bearing rock, including simulation of radio frequency wave confinement within the hydrocarbon-bearing rock, at several frequencies and temperatures. A frequency for retorting is selected based upon simulation results. Radio frequency couplers are installed into at least one borehole in the hydrocarbon-bearing rock and driven with radio frequency energy to heat the hydrocarbon-bearing rock. As the rock heats, it releases carbon compounds and these are collected.



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SYSTEM AND METHOD FOR EXTRACTION OF HYDROCARBONS BY IN-SITU
RADIO FREQUENCY HEATING OF CARBON BEARING GEOLOGICAL
FORMATIONS

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RELATED APPLICATIONS

[0001] The present application claims the benefit of priority to Provisional Application Serial No. 60/976,314 filed September 28, 2007, and is incorporated herein by reference.

Field

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[0002] The present apparatus and method relates to the extraction of hydrocarbons from hydrocarbon-bearing geological formations. In particular, the method is applicable to extraction of hydrocarbons from oil-shale and tar sands, and may also be useful in enhanced oil recovery from oil fields.

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BACKGROUND

Formations Bearing Low Motility Carbon Compounds

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[0003] Many carbon and hydrocarbon-bearing geological formations contain carbon-containing compounds that lack sufficient mobility for tapping with simple wells. For example, oil-shales, tar sands, hydrocarbon-bearing shale, and low-grade coal are carbon-bearing sedimentary rocks containing carbon compounds that do not migrate efficiently into wells for recovery under ordinary conditions.

25

[0004] Oil shale is a general term applied to a group of fine black to dark brown shale rich enough in low motility or non-mobile organic material (called kerogen) to yield petroleum-like oil upon retorting. The kerogen in oil shale is converted to oil through pyrolysis. During pyrolysis the oil shale is heated to temperatures in the range 250–500 °C in the absence of air. The kerogen is converted to oil and separated out, a process called "retorting".

Retorting

30

[0005] The kerogen in oil shale is converted to oil through retorting. During retorting the oil shale is heated to temperatures in the range 250–500 °C in the absence of air. Some volatile components of the kerogen may evaporate or liquify and can be

recovered. Other components of the kerogen may pyrolyze into shorter chain hydrocarbons that can then also be recovered from the shale. The net effect is that retorting converts some or all of the kerogen to oil that is then separated out. Additionally, residual carbon compounds in hot rock, including oil shale, coal, or coke,
5 can react with water and/or hydrogen to produce recoverable gasses and hydrocarbons in reactions akin to those that occur during liquefaction of coal.

[0006] Extracting kerogen from carbon-bearing sedimentary rock in such formations has been accomplished by mining the rock. Once the rock is mined, it may be retorted using temperatures at the higher end of the range in a retort to extract
10 hydrocarbons; alternatively the kerogen in some such rocks can be burned directly in a furnace. Spent rock must then be disposed of. This process of mining and surface retorting is also known as "ex-situ retorting". Ex-situ retorting is widely recognized as posing considerable environmental problems due to the surface disturbance involved with mining and disposal of spent rock; it also requires much labor and heavy machinery.

15 [0007] Some companies have experimented with "in-situ retorting." This process extracts carbon compounds by heating carbon-containing rock while it is essentially intact and still in place in a formation. In-situ retorting offers potential advantages in that labor and machinery required, as well as environmental damage associated with mining and spent rock disposal, are all potentially reduced.

20 [0008] Other companies have experimented with "modified in-situ retorting" wherein a portion of rock is mined to create voids in the formation, the mined rock being subjected to ex-situ retorting. In modified in-situ retorting, rock remaining in the formation after mining is rubbleized into the voids, the un-mined rubble is then heated to extract carbon compounds.

25 [0009] In-situ and modified in-situ retorting experiments have not been wholly successful.

Deposits

[0010] Thousands of acres of oil-shale deposits having deposit thickness from 500 to 2000 feet covered by from 500 to 1000 feet of overburden, exist in the Green
30 River formation of Colorado, Utah, and Wyoming. In some places these deposits rise to the surface. The Green River deposits contain carbon compounds in kerogen form,

yielding from 15 to over 50 gallons of hydrocarbons per ton when assayed through mining and surface retorting.

[0011] The Green River deposits, together with other sedimentary rock deposits bearing low-motility carbon compounds worldwide, including large oil shale deposits in Canada, and some deposits in other countries, represent a substantial reserve of carbon compounds. Mining and surface retorting of these deposits has many potential environmental consequences, risks, and costs. It is desirable to find a way to efficiently extract carbon compounds from these carbon-bearing rocks that does not require mining.

10 **Shell's In-Situ Retorting Process**

[0012] U.S. Patent 7,225,866 to Berchenko, et al., hereinafter Berchenko, assigned to Shell oil, discloses, in 320 pages incorporated herein by reference, methods of increasing the motility of carbon compounds in some oil shale formations by heating the formation in place using electrical resistance-heated heating wells. As the formation's temperature increases, some carbon compounds in the formation are retorted, mobilizing through a effects including the decrease in viscosity of hydrocarbons with increased temperature, melting of some solids, vaporization of volatile compounds, as well as decomposition into lighter molecular weight, more mobile, compounds through anhydrous and hydrous pyrolysis – this high temperature process in rock still in place in the formation is known as in-situ retorting. Berchenko then taps the mobilized compounds as liquid and gas with production wells separate from those through which heat is applied to the formation. The method of Berchenko may require that from seven to more than twenty times as many heating wells as production wells be drilled into the formation. (Berchenko, claims 1, 8, 14, and 16)

[0013] In a Shell Oil embodiment, a freeze wall is constructed to seal off groundwater by drilling 2000' wells, eight feet apart, around the perimeter of a 10 acre working zone, and then circulating a super-chilled liquid into those holes to freeze the ground to -60°F. The working zone is then largely dewatered to control humidity and avoid excess steam production during retorting. Recovery wells are drilled on 40 foot spacing within the working zone.

[0014] A large number of helical heating wells, from 7 to 20 or more times as many heating wells as production wells, are drilled in a pattern around the production wells. When 7 times as many heating wells as production wells are used, Berchenko discloses these heating wells as about eight to fifteen meters from the production wells.

5 An electrical heating element is lowered into each heating well and allowed to heat the kerogen to 650 (aprox 340 C) to 700°F (aprox 370C) over a period of one to four years, slowly converting it into oils and gases, which are then pumped to the surface. Once the formation is well heated, Berchenko also discloses a possibility of injecting oxidizer into heating wells to further heat the formation by combustion in place.

10 [0015] The *in-situ* method of Berchenko requires close to 100% surface disturbance, greatly increasing the footprint of extraction operations in comparison to conventional oil and gas drilling, in part because of the large number and close spacing of freeze-wall, heating, and production wells required.

[0016] Berchenko also summarizes other techniques that have been proposed, and in some cases tried, for in-situ and modified in-situ retorting of oil shale formations. These methods range from heating of formations by combustion through injection of oxygen-rich gas into heating wells to detonating nuclear weapons within the formation.

Heavy Oil and Tar Sands

20 [0017] Heavy oil and oil sands occur world-wide, but the two largest known deposits are the Athabasca Tar Sands in Alberta, Canada and the Orinoco extra heavy oil deposit in Venezuela. Some tar sand deposits exist in the United States. Much deep off-shore oil is heavy oil as well. The bitumenous hydrocarbon content of these deposits is relatively immobile under ordinary conditions, such that primary recovery is slow and may yield less than eight percent of the hydrocarbon content of the rock. Such oil is sometimes recovered with cyclic steam stimulation or steam assisted gravity drainage, both techniques involving use of steam to heat a formation to encourage flow of heavy oil.

Enhanced Oil Recovery (EOR)

[0018] Typically only 20-30 percent of a reservoir's original crude oil content can be pumped out of the sand through simple drilling, this is primary recovery.

Secondary recovery, typically involving injecting water under pressure, yields another
5 10-20 percent; however, this water can present a significant waste disposal problem as the water may be pumped out of the well with the oil. Tertiary recovery may also be used, often involving liquid carbon dioxide injected under pressure; this acts as a solvent, reducing the oil's viscosity and allowing a little more recovery.

[0019] EOR is a generic term for techniques, including secondary and tertiary
10 recovery, for increasing the amount of oil that can be extracted from an oil field. Using EOR, 30-60 %, or more, of the reservoir's original oil may be recovered.

[0020] Gas injection is a commonly used EOR technique. Here, gas such as carbon dioxide (CO₂), natural gas, or nitrogen is injected into the reservoir whereupon it expands and thereby pushes additional oil to a production well-bore, and moreover the
15 gas dissolves in the oil to lower its viscosity and improves the flow rate of the oil. Oil displacement by CO₂ injection relies on the phase behavior of CO₂ and crude oil mixtures that are strongly dependent on reservoir temperature, pressure and crude oil composition. These mechanisms range from oil swelling and viscosity reduction for injection of immiscible fluids (at low pressures) to completely miscible displacement in high-pressure
20 applications. In these applications, more than half and up to two-thirds of the injected CO₂ returns with the produced oil and may be re-injected into the reservoir. The remainder is trapped in the oil reservoir by various means.

[0021] Other techniques for EOR include thermal recovery (where heat reduces viscosity of hydrocarbons in the formation to improve flow rates), and chemical
25 injection, where polymers and/or detergent-like surfactants are injected to help lower the surface tension that often prevents oil droplets from moving through a reservoir, thereby increasing effectiveness of water floods.

[0022] EOR techniques, including thermal recovery and gas injection, can benefit from the controlled application of heat to the reservoir.

Volumetric Heating of Carbon-Containing Formations by Radio Waves

[0023] The concept of volumetric heating by radio waves (radio frequency processing) of oil shale was developed by Illinois Institute of Technology and Raytheon in the late 1970s. The concept was to heat modest volumes of shale over a period of time using vertical electrode arrays driven by high-power radio-frequency AC sources. The radio-frequency energy is expected to propagate into and through the formation, where much of it will be absorbed by the formation – resulting in heating of the formation.

[0024] United States Patents 4135579, 4140179, 4196329, 4301865, 4320801, 4457365, 4485869, 4487257, 4508168, and 4583589, disclose this concept of using a variety of electrode and radiator assemblies. Of these, U.S. patents assigned to Raytheon, including 4508168, 4583589, and 4457365, describe combined production well and coaxially-fed radiator assemblies, that provide better vertical control of radiation than experimental predecessors (background 4508168, 4583589). Patents 4135579, also assigned to Raytheon, describes heating of formation rock by conducting radio frequency currents between two or more electrodes inserted into a formation. Patent 4140179, assigned to Raytheon, describes use of a pattern of radiator wells and production wells, where substantial heating is reported at distances of over 25 feet from the radiator wells once water is driven from the formation.

[0025] The Raytheon and Illinois Institute studies have shown that the dielectric constant and absorption, hence the impedance, of formations change as they are heated and substances like water are expelled from them. This effect also results in changes to the wavelength of electromagnetic radiation in the formation. Further, typically a length of radiator that is of length $1/6$ to $1/7$ wavelength in air is approximately half a wavelength in a formation.

Rough Wall Waveguides

[0026] A named inventor has published an article on modeling rough-walled waveguides; although the article assumed perfect conductors for side plates of the waveguide. This article is entitled “Probability-density function for total fields in a straight PEC (perfect electrical conductor) rough-wall tunnel,” Hsueh-Yuan Pao, Microwave and Optical Letters, vol 46 issue 2, pp 128-132, 26 May 2005; the contents of

which are incorporated herein by reference, and known hereinafter as “The Pao Rough-Wall article.”

[0027] Another article on computer modeling lossy rough-walled waveguides has been published as “Full Wave Analysis of RF Signal Attenuation in a Lossy Rough Surface Cave using a High Order Time Domain Vector Finite Element Method,” J. Pingenot, et. al, Progress in Electromagnetics Research (PIERS) 2006, presented March 26 through March 29, 2005, Lawrence Livermore Laboratory document UCRL Proc 216990 dated 10 Nov 2005, the contents of which are incorporated herein by reference, and hereinafter known as “The Pingenot Lossy Rough Surface Cave article”.

<<http://www3.interscience.wiley.com/cgi-bin/abstract/110503149/ABSTRACT?CRETRY=1&SRETRY=0>>

Waveguides Applied to In-Situ Retorting

[0028] Burnham, “Slow Radio Frequency Processing of Large Oil-Shale Volumes to Produce Petroleum-Like Shale-Oil”, Lawrence Livermore Laboratory publication UCRL ID 155045, describes an IIT Research Institute proposal to place three rows each having numerous vertical, closely-spaced, conductors into holes drilled into a formation, this is further described in U.S. patent 4485869.

[0029] The conductors in each row are tied together to form what becomes effectively three large, parallel, plates, serving as an artificial “tri-plate waveguide” enclosing a volume of rock. The enclosed volume of rock is then heated by RF energy coupled into this artificial waveguide structure. Burnham, in his FIG. 2, also describes a horizontal variation of this proposal, where artificial conductors are placed into closely-spaced horizontal holes drilled into the formation on three levels; the conductors on each of the three levels being connected together to form a plate of a horizontal tri-plate waveguide.

Summary

[0030] A method of producing liquid hydrocarbons from a hydrocarbon-bearing rock in situ in a geological formation begins with exploring the formation by drilling a plurality of boreholes into the formation and taking core samples of the

hydrocarbon-bearing rock and at least one overburden layer. Electrical parameters of the hydrocarbon-bearing rock and the overburden layer are determined, as well as a roughness of a boundary between the hydrocarbon-bearing rock and the at least one overburden layer. These electrical parameters are used to construct a computer model of a portion of the hydrocarbon-bearing rock and at least one overburden layer, the computer model based upon modeling the formation as a rough-walled waveguide. This computer model is used to simulate propagation of radio frequency energy within the hydrocarbon-bearing rock, including simulation of radio frequency wave confinement within the hydrocarbon-bearing rock, at several frequencies and temperatures. A frequency for retorting is selected based upon simulation results. Radio frequency couplers are installed into at least one borehole in the hydrocarbon-bearing rock and driven with radio frequency energy to heat the hydrocarbon-bearing rock. As the rock heats, it releases carbon compounds and these are collected.

BRIEF DESCRIPTION OF THE FIGURES

[0031] FIG. 1, a cross section illustrating a formation with overburden and underlying formations.

[0032] FIG. 2, an illustration of measured electrical parameters of rock.

[0033] FIG. 3, a flowchart of a method of producing shale oil by in-situ retorting.

[0034] FIG. 4, frequency response of imaginary part of permittivity in Cole-Cole model

[0035] FIG. 5, an example of a Cole-Cole diagram.

[0036] FIG. 6 is a top view of a production field.

[0037] FIG. 7 is a cross section of a production field.

[0038] FIG. 8 is a schematic diagram of an embodiment of a coupler for applying radio frequency energy to a hydrocarbon-bearing formation.

[0039] FIG. 9 is a schematic diagram of an alternate embodiment of a coupler for applying radio frequency energy to a hydrocarbon-bearing formation.

[0040] FIG. 10 is a schematic diagram of a system that applies power selectively to subunits of the carboniferous formation, each acting as a discrete waverguide.

[0041] FIG. 11 is a schematic diagram of an alternate embodiment of a coupler for applying radio frequency energy to a hydrocarbon-bearing formation.

[0042] FIG. 12 is a schematic diagram of a system that applies power selectively to subunits of the carboniferous formation, each acting as a discrete waverguide, and repeats this for a second carboniferous formation.

DETAILED DESCRIPTION OF THE EMBODIMENTS

RF Properties of Oil and Rock

Conductive rock

[0043] Generally, overburden and underlying rock layers tend to have larger water content than hydrocarbon-bearing formations do. Since water, especially salty water, tends to have greater conductivity than dielectric rock, these formations are for purposes of this document often classifiable as conductive rock.

Dielectric rock

[0044] Dielectric rock is rock that is a less conductive media than is conductive rock. This is often because presence of large amounts of nonpolar organic compounds tends to exclude conductive water from the formation.

Boundaries

[0045] Reflection and leakage takes place as a RF wave propagates across at the interface from one medium to another medium if the media differ in electrical properties. The different electrical properties of the media are distinguished by the constitutive parameters permittivity ϵ , permeability μ , and conductivity σ .

[0046] For the most dielectric media, permittivity is the significant parameter to describe the energy reflection and transmission at the interfaces. Therefore we can ignore the permeability and conductivity for most dielectric media. To confine radio frequency energy inside of a conductive medium, we want leakage from the formation

minimized, while maximizing energy reflections from interfaces back into the conductive media.

[0047] Hydrocarbon-bearing earth formations occur because of a unique set of geologic conditions, therefore underlying and overlying rock formations surrounding the hydrocarbon-bearing earth formations were formed under different conditions and have different characteristics than the hydrocarbon-bearing formation.

[0048] Reflection and leakage are also be affected by characteristics of the interfaces themselves, including a degree of roughness of the interface

[0049] Rock's electrical properties vary with frequency as well as the constituent properties of the rock. In some rock formations, there may not be a significant difference in the electrical properties between the hydrocarbon-bearing earth formations and the surrounding formations; at other frequencies, the difference can be much larger. Further, as published in the aforementioned Raytheon patents, some electrical properties of rock can be expected to change as the rock is heated, in part because water may be driven out of the rock.

Analyzing the Formation

[0050] FIG. 1 illustrates a cross section of an oil-shale field. FIG. 3 is a flow chart of a method for developing an oil-shale field. FIG. 2 is taken from Sternberg and Levitskaya, 2001, Electrical parameters of soils in the frequency range from 1 kHz to 1 GHz, Radio Science, Vol. 36, No. 4, Pages 709-719; It presents the relative permittivity measured from Avra Valley, Arizona, and represents typical soil and rock electric properties. This Figure shows the wide range of electrical properties that occur in typical soils and rocks.

[0051] With reference to FIGs. 1 and 3, The field may be mapped initially with a seismic study 202 or use of other well known petrophysical mapping tools (not shown) that are known in the art, such as the interpretation of logs or gravimetric studies. In seismic studies, sound wave vibrations are propagated into the ground, as these strike impedance mismatches associated with various interfaces between layers, such as interfaces between overburden layers 102, 104, 106, the oil shale hydrocarbon-bearing formation 108, and underlying layers 110, some sound is reflected. Seismic studies can

provide information about the depth of various interfaces, and hence the layers, as well as an indication of roughness of the interfaces.

[0052] Wells may be drilled 204. Electrical properties, including permittivity ϵ , permeability μ , and conductivity σ , of rock surrounding the well may be measured with
5 electromagnetic well logging 206 as known in the art, and core samples 208 may be taken from each formation drilled through, including particularly core samples from the lowest layer of overburden 106, the hydrocarbon-bearing formation 108, and uppermost underlying layers 110. From these samples, assays for potential yield may be performed and the hydrocarbon-bearing formation positively identified 210.

10 [0053] Since the electrical properties measured with logging represent properties as they currently exist in the formation, and these are known to change with temperature, electrical properties of core samples are determined 212 both under room conditions and as these samples are heated.

[0054] Since properties, including permittivity ϵ , permeability μ , and
15 conductivity σ , may vary with frequency as well as temperature, these parameters are measured at a variety of frequencies.

[0055] Simulations of the field distribution between hydrocarbon-bearing earth formations and surrounding rock have been performed for some possible sets of electrical parameters of these layers. The typical results for the rock surrounding the
20 hydrocarbon-bearing earth formations is in the 20% of field strength, while 80% of field strength remains inside of hydrocarbon-bearing earth formations. It is clear that the field strength in the surrounding rock is much smaller than inside of the oil shale. With this electrical difference between the layers, a quasi guide wave structure is in place.

[0056] The bigger the permittivity contrast between layers, the stronger the
25 reflection will take place at the interface for the dielectric rock. However this contrast will vary with frequency and may be absent at some frequencies and temperatures because the earth's electrical properties vary with frequency.

Cole-Cole Parameters

[0057] In order to predict how far electromagnetic radiation will penetrate
30 into the formation, and predict where heating will take place, simulations using the Cole-

Cole model are used. This requires that Cole-Cole model parameters be determined from properties of the hydrocarbon-bearing rock formation.

[0058] The sum of the real and imaginary parts of the dielectric permittivity represents all of the energy in the system on a per cycle basis. At low frequencies, all the energy is asymptotically going into storage. At the frequency of maximum movement, some energy is going into storage but most is lost to dissipation. At the highest frequencies, all the energy is asymptotically going into storage, but the total is smaller as shorter distances of charge separations occur compared to the low frequency limit.

[0059] The frequency of maximum movement defines the time constant of the system. These systems are over damped harmonic oscillators, also known as diffusion-limited relaxation processes. The general form of the model that describes the frequency dependence of such systems is the Debye-pellat relaxation equation:

$$\varepsilon' - i\varepsilon'' = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + i\omega\tau}$$

where ε' is the real part of the dielectric permittivity, ε'' is the imaginary part of the dielectric permittivity, ε_{∞} is the high frequency limiting value of the permittivity, ε_s is the low frequency limiting value of the permittivity, ω is radian frequency, and τ is the relaxation time constant. The frequency of maximum movement and loss occurs at $f = 1/\tau$. The time constant often describes the size of something such as grain or pore sizes that is limiting the motion of the charge which is other than the field disequilibrium.

[0060] In general, single relaxations are rarely observed in natural systems. Instead, there are distributions of relaxations corresponding to distributions of size scales that influence movement of charge. There are several equations describing such distributed systems, with the most common experimental observations in agreement with the model from Cole and Cole:

$$\varepsilon' - i\varepsilon'' = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + (i\omega\tau)^{\alpha}}$$

where α describes the breath of the time constant distribution. Multiple Cole-Cole equations may be summed to describe a series of different polarization process. These processes typically vary considerably with environmental influences such as temperature, pressure, and chemistry.

[0061] FIG. 4 shows a typical frequency response of imaginary part of the permittivity ϵ'' of Cole-Cole model plot, which represents the dielectric loss of the media. It is clear that there is a maximum about 120 MHz. The maximum loss, which is associated with the maximum RF energy absorption, takes place at that frequency.

5 [0062] Using the Cole-Cole model facilitates finding the optimal heating frequency. The Cole-Cole parameters are usually determined experimentally. One can use standard numerical data fitting algorithms to find the parameters. When plotted on a real-imaginary plot, the arc center, radius, and end points can be directly related to these parameters. Wideband data are needed to uniquely determine the parameters, i.e. a
10 significant part of the arc must be displayed on the real/imaginary plot. Sternberg and Levitskaya described how to use graphical method to determine the Cole-Cole model from the measured data, and how to obtain these data experimentally (B. K. Sternberg and T. M. Levitskaya, Electrical parameters of soils in the frequency range from 1 kHz to 1GHz, using lumped-circuit methods, *Radio Science*, July/August 2001, pp 709-719).

15 FIG. 5 shows a typical Cole-Cole diagram.

[0063] Specific samples of the hydrocarbon-bearing earth formations that we are interested in must be measured to determine 212 the Cole-Cole parameters for that rock material at normal and elevated temperatures.

[0064] Since the relaxation time τ of the hydrocarbon earth formation and the
20 overburden (top) and bottom (underlying) rock layers are different, the relaxation frequency for maximum thermal conversion in the hydrocarbon earth formation is different within each of the carboniferous, top, and bottom layers. It is this difference that results in the large contrast in the permittivities between the hydrocarbon earth formation and top and bottom rock layers. This constructs a natural waveguide structure that can
25 confine the bulk of electromagnetic energy inside hydrocarbon-bearing earth formations by reflecting energy back into the formation when energy strikes a boundary with overburden or underlying layers.

Non-linear operation means both conductive heating and dielectric heating exist

[0065] Since the applied RF power is extremely high, the non-linear
30 phenomenon will take place. In addition to the dielectric heating, the conducting heating will take place in this scenario. There is usually little free charge in dielectric media--

where most charges are bound in the molecules or atoms. However, the bound charges will escape from molecules or atoms, as they absorb enough energy, if the applied external RF power is extremely high. We attribute this free charge flow, which ultimately forms the conductive current, to the non-linear effect. The conductive current will cause the conductive loss. It is this conductive loss that converts the addition RF energy into thermal energy.

Modeling the Formation and Determining Frequency

[0066] A model of the formation, including the interfaces with the lowest layer of overburden and the highest underlying layer is then constructed 214. The model includes Cole-Cole parameters to determine absorption, thus indicating a range of RF energy penetration into the formation. The model further includes a model of the formation as a natural, in situ, waveguide incorporating into the model layer constitutive parameters permittivity ϵ , permeability μ , and conductivity σ and a model of surface roughness for each boundary between layers; this model is used for modeling reflections at the boundaries between the carboniferous formation 108, the lowest layer of overburden 106, and the highest layer of underlying rock 110. This lossy waveguide model is based upon those presented in the “The Pingnot Lossy Rough Surface Cave article” and “The Pao Rough-Wall article.”

[0067] Simulations are performed 216 on this model to determine an optimum frequency at which most RF energy coupled into the formation will be confined to the carboniferous formation 108, while providing desired penetration of RF energy into the formation.

[0068] An optimum operational frequency is then selected 216. We expect that the operational frequency will be different for every field, but within the range of 0.5MHz to 500MHz, this range of frequencies is hereinafter known as radio frequencies.

[0069] It is known that electromagnetic energy may reflect when striking some boundaries at certain angles of incidence, while it will penetrate the boundary when striking at different angles of incidence. These angles are determined from the simulations 216.

Freeze Wall

[0070] Refer now to FIG. 6, which gives a top view of a portion of production field 600, FIG. 7 which gives a cross section of a production field, as well as FIG. 2. The water table varies in depth, sometimes dramatically, throughout the western United States. Excessive water entering the carboniferous formation is undesirable since it can require large amounts of energy to boil this water. While in some areas it may be possible to avoid excessive water incursion without a freeze-wall 605 of frozen ground, in other locations a freeze-wall may be needed to limit the amount of water that enters a production zone during the lengthy retorting process. Need for a freeze wall is determined 222 based in part upon hydrology of the location and on depths of the hydrocarbon-bearing rock; a freeze wall is likely needed if the hydrocarbon-bearing formation is below the water table.

[0071] If a freeze-wall is needed, rows of wells 602 are drilled and chilled by a freezer 603 to create 224 a freeze-wall 605 in manner similar to that described by Berchenko.

Inserting Probes to Excite the Formation

[0072] Coupler probes 620, 622 are inserted 226 through wells 604 into the carboniferous formation 108 in order to couple electromagnetic energy into the formation. More than one primary coupler probe 620 in wells 604 may be used, since additional probes driven with appropriate phase may give good control of a pattern of heating in the formation 108. Where simulation of boundaries between carboniferous formation 108, lowest overburden 106, and underlying formations 110 showed large angle of incidence where energy is reflected back into the carboniferous formation 108, these coupler probes may be simple quarter-wave rod or half-wave dipole couplers placed 226 in vertical well bores.

[0073] Where the layer of lowest overburden 106 is not sufficiently conductive to serve as a groundplane for a quarter-wave rod coupler, a coupler as illustrated in FIG. 8 may be used to help minimize shield currents in the coaxial transmission line and thereby minimize heating of the overburden. A radio-frequency source 702 drives a coaxial transmission line 706 through impedance matching apparatus 704. At the boundary between the lowest layer of overburden 106 and the carboniferous

formation 108, the coaxial transmission line 706 terminates in a coupler 708 that may incorporate matching circuitry. At this coupler 708, at least four ground-plane rods 710 are driven radially into the rock outward from the borehole, these should be at least electrically one fourth wavelength long and are electrically coupled to the shield of the coaxial transmission line 706. At this coupler 708 a coupling rod 712, electrically coupled either directly or through a matching transformer to the center conductor of the coaxial transmission line, is driven into the carboniferous formation 108.

[0074] Where simulations show that a shallow angle of incidence is required for most of the radio frequency energy to be reflected back into the carboniferous formation 108, couplers each having a colinear array of two or more dipole elements, such as that of FIG. 9, and capable of improved vertical directivity may be placed in similar vertical wells 604. Each dipole element, such as dipole element 802 and 804, may be fed through an appropriate balanced-to-unbalanced (balun) matching transformer 806, as known in the art of antennas, in turn driven through coaxial transmission lines 810 from a high-power radio frequency source 812 through a matching circuit 814 located on the surface. In this embodiment, a phase of one dipole element, such as dipole element 804, may be adjusted by a phase shift device 816 to more precisely control and adjust a pattern of radio frequency energy propagating into the carboniferous formation. The phase shift device may be as simple as a short length of transmission line.

[0075] A single vertical coupler will introduce electromagnetic fields that will radiate in all directions in the horizontal plane in the formation. Where directivity in the horizontal plane is desired, as for example to protect a freeze wall 605 from being melted by applied RF energy, additional protective couplers, or protective probes 622, may be placed in additional vertical wells 606 spaced near half a wavelength of the selected frequency in the carboniferous formation 108, and driven with appropriately phased signals 230, such that almost of the radio frequency energy propagates in a preferred direction through the formation 108 into a heated zone 120 of the carboniferous formation that will become a production zone when retorting temperatures are reached, and that little radio frequency energy propagates in other directions in the formation.

[0076] As each coupler is lowered into position, return losses at the selected frequency are measured, and adjustments are made to the couplers, balun transformers, and above-ground impedance-matching circuitry as necessary.

Retorting the Formation *In situ*

5 [0077] Once the probes and associated protective probes have been inserted, raising the temperature of the formation may begin. Radio frequency energy is applied 230 from RF sources 607 to the formation 108 through the probes in driven 604 and protective wells 606 and appropriate, adjustable, impedance-matching circuitry. This energy need not be applied continuously, since the formation has sufficient heat capacity 10 to integrate it; this permits use of lower-cost nighttime power. Sufficient energy is applied over a period of time to raise the formation 108 to retorting temperatures.

[0078] Since electrical characteristics of the formation 108 will change as water is driven out and temperature rises, impedance mismatches and standing wave ratios at the radio frequency sources, and standing wave ratios in the coaxial transmission 15 lines, as well as heating of the formation 108 and penetration of the radio frequency power through the formation 108 are monitored 234 every twelve to forty-eight hours, or another time interval as may be useful to facilitate the conduct of operation..

[0079] When necessary, radio frequency power frequencies and/or the probe structure may be adjusted 234. Lengths of coupler elements changed, turns ratios in 20 balun transformers altered, or adjustments made to parameters of the impedance-matching circuitry to maintain good coupling of radio frequency power into the formation.

Producing the Products

[0080] As the formation heats to, and is maintained at, retorting temperatures 25 in the 250 to 400° C range, liquid and gaseous products will begin to accumulate and can be removed either through separate production wells 608, or through inserting production equipment in the driven 604 and protective 606 wells along with the couplers. The resultant liquids and gasses may be produced 238 by conventional wells, as are known in the art. Interference of production wells and production equipment with the radio 30 frequency fields in the formation 108 may be prevented by using nonconductive materials or by segmenting metallic materials such as pipe into non-resonant lengths with insulated

bushings between. Since there will be a tendency for rock near the driven wells 604 to heat somewhat faster than rock elsewhere in the field 600, an early production well 610 may be installed near them. Fluids and gasses from production wells 608, 610, are piped to collection and condensing equipment for handling the expected liquid, vapor, and gaseous products.

[0081] It is anticipated that driven 604 wells will occur in clusters to permit directional control of the radio frequency fields in the formation 108, and that clusters may be spaced as far as 100 meters apart.

[0082] Some products removed from the formation 108 as vapor, including many hydrocarbons in the gasoline range, may be condensed into liquid form at the surface. Many liquids and condensable vapors, as well as noncondensable gasses, may be transported to market for sale, while some may be consumed on-site to provide power for the radio-frequency sources and to maintain the freeze-wall, if a freeze-wall is needed.

Heavy Oil extraction and upgrade

[0083] The technology presented above is able to heat a formation to lower the viscosity of hydrocarbons, separate unwanted elements or compositions within a hydrocarbon bearing deposit, and extract the desirable hydrocarbons. In this regard, there is no need to release materials that are trapped or bound in shales. The instrumentalities described herein may be used in porous reservoirs of sandstone, heavy oil sands, dolomite, limestone, silt, chalk, etc. to replace or complement steam flooding in the reduction of viscosity to accelerate production rates. In some instances, such as the Athabasca Tar Sands, these materials may now be retorted in situ, such that the need for mining is lessened or eliminated.

[0084] For heavy oil or tar sand recovery applications, radio frequency heating to a temperature above 150°C but not higher than 200°C, using methodology as described above but without need of a freeze-wall, is used to reduce the viscosity of the in-situ tars or heavy oils. The invention presented can perform some enhanced oil recovery alone; or it can use with other existing EOR technologies to achieve the more efficient recovery rates.

[0085] Partially or completely pyrolyzing the tars or heavy oil in-situ, by maintaining the formation at elevated temperatures for extended times, could upgrade the hydrocarbon products cost effectively and environment friendly. RF energy is applied as above described to heat a relatively large block of tar sands or heavy oil in-situ. As the temperature of the tar sands or heavy oil increases above 100°C, the inherent moisture begins to change into steam. A further increase in temperature to around 150°C substantially reduces the viscosity of in-situ tar sands or heavy oils. As the pyrolysis temperature in the 200 to 300 C range is approached, the higher volatiles are emitted until complete pyrolysis of the in-situ fuels is accomplished.

Extract the crude from deep offshore

[0086] The invention presented in previous sections also applies to the extraction of heavy crude oils from deep offshore.

Enhance the recovery oil from stripper wells

[0087] The technologies presented in previous sections apply to enhance recovery oil from partially depleted petroleum reservoirs. Usually there is still 80% remaining organic products in the partially depleted petroleum reservoirs. High viscosity and low permeability of rock lower recovery rate below the economic threshold set by the petroleum industry. Employing our technology to heat the formation, used along with other enhanced recovery technology, allows recovering remaining organic products from these partially depleted petroleum reservoirs.

Selective emitter design

[0088] Fig. 10 an emitter array 1100 positioned a borehole 1102 through carboniferous formation 108. The array 1100 is formed using individual emitter elements 1104, 1106, 1108, 1110 that are separated by isolation elements 1112, 1114, 1116, 1118. By way of example, the emitter elements 1104, 1106, 1108, 1110 may be made of metal, and the isolation elements of a high strength ceramic material having a high dielectric constant. The respective emitter elements and isolation elements may use threaded pin and box couplings as are used on drill pipe, except the isolation elements form a

nonconductive barrier between the emitter elements. An external dielectric coating 1119 may isolate the emitter elements 1104, 1106, 1108, 1110 from one another and from conductive fluids in borehole 1102 along the entire length of the emitter array 1100 or selected portions thereof..

5 [0089] Cable bundle 1120 contains a plurality of transmission lines 810, such that the respective dipole elements of Fig. 9 are coupled to drive a corresponding conductor rods coupler similar to that of Fig. 9, but set up in a series configuration. Each dipole element 802, 804, etc. . . are coupled to drive a corresponding one of the emitter elements 1104, 1106, 1108, 1110. By way of example, dipole element 802 by be
10 configured to drive emitter element 1104. Dipole element 804 may be coupled to drive emitter element 1106. Additional dipole elements (not shown) may be provided to drive the remaining emitter elements. Balun 806 may be located within emitter element 1106. The multi-emitter design is useful because producing formations are most often not homogenous. Thus, carboniferous formation 108 may be formed of discrete subunits
15 108A, 108B, 108C, 108D. Each subunit may be separated from other subunits by waveguide boundaries, such as boundaries 1122, 1124. These boundaries may be detected by using conventional petrophysical tools to log the formation. Such tools include, without limitation, induction logging tools, gamma ray and neutron logging tools, microwave logging tools, acoustic logging tools, well logs that represent cuttings
20 obtained while drilling, and combinations of the foregoing tools. Techniques for the analysis and interpretation of data obtained from use of these tools is well known and conventional in the art. Thus, power can be more selectively applied to discrete intervals of carboniferous formation 108, such as where emitter 1106 provides emanation 1126 to subunit 108B and emitter 1108 provides emanation 129 to subunit 108C. IN this
25 manner, power may be selectively applied to protect groundwater, for example, where subunits 108A, 108D border aquifers. It is also possible to apply power to subunits 108B and 108D while not applying power to subunit 108C. In this manner, energy costs may be saved if it would be unproductive to heat subunit C, or if for environmental or other reasons it is not desirable to heat subunit C except by conductive heating from subunits
30 108B and 108D. The subunits 108A through 108D may each be of any thickness, such as several meters thick, tens of meters thick, or hundreds of meters thick.

[0090] It is also possible to configure the circuitry of Fig. 9 in parallel, as shown in Fig. 11. The RF source 1108 proceeds to matching circuitry 1102, but this time drives a common transmission line 1104 that serves as a rail for a plurality of phase shift and balun circuitry components 1106, 1108, 1110, etc. . . .that unbalance the matching transmission to make power available from the respective emitter elements 1104, 1106, 1108, 1110 each associated with their own respective phases. Here the phase shifting prevents the respective emitters of the array 1100 from acting in combination as a single antenna. .

[0091] In the embodiments of Figure 11 it is desirable to place each of circuitry components 1106, 1108, 1110, etc., and its associated emitter elements 1104, 1106, 1108, 1110, etc. into a separate formation subunit. such as subunits 108A through 108D. Alternatively, a radiative pattern concentrating more of the effective radiated power into each formation may be obtained by placing two or more baluns 1106, 1108, 1110, etc., and their associated emitter elements 1104, 1106, 1108, 1110, etc. in each of several formations for which heating is desired if an appropriate phase shifting network is provided at all but one balun of each formation.

[0092] As shown in FIG. 12, the foregoing concepts may be combined where power from the RF source 1200 proceeds through matching circuitry 1202 onto transmission line 1204. In a first carboniferous formation 108', a first balun 1206 drives a first emitter element (not shown) that is separated in space and phase domains from a first phase and balun component 1208. Here the transmission line 1204 extends through intervening rock 1210 to a second carboniferous formation 108'' to drive also a second balun and a second phase and balun circuitry component 1214. In this instance, the intervening rock 1210 is sufficiently thick to prevent the electrical components within formations 108' and 108'' from acting as a single antenna.

[0093] While the forgoing has been particularly shown and described with reference to particular embodiments thereof, it will be understood by those skilled in the art that various other changes in the form and details may be made without departing from the spirit and hereof. It is to be understood that various changes may be made in adapting the description to different embodiments without departing from the broader concepts disclosed herein and comprehended by the claims that follow.

CLAIMS

What is claimed is:

1. A method of producing liquid hydrocarbons from a hydrocarbon-bearing
5 rock in situ in a geological formation comprising:
drilling a plurality of boreholes into the formation and taking core samples of the
hydrocarbon-bearing rock and at least one overburden layer therefrom;
determining electrical parameters of the hydrocarbon-bearing rock and the overburden
layer;
10 performing a seismic study to determine a roughness of a boundary between the
hydrocarbon-bearing rock and the at least one overburden layer;
constructing a computer model of electromagnetic properties of a portion of the
hydrocarbon-bearing rock and at least one overburden layer, the computer model
based upon modeling the formation as a rough-walled waveguide;
15 using the computer model to simulate propagation of radio frequency energy within the
hydrocarbon-bearing rock, including simulation of radio frequency wave
confinement within the hydrocarbon-bearing rock, at a plurality of frequencies;
selecting a frequency of the plurality of frequencies;
placing a first radio frequency coupling apparatus into at least one borehole in the
20 hydrocarbon-bearing rock;
driving the first radio frequency coupling apparatus with radio frequency energy to heat
the hydrocarbon-bearing rock; and
collecting carbon compounds released from the rock.
2. The method of claim 1, wherein the hydrocarbon-bearing rock is oil shale.
- 25 3. The method of claim 2, further comprising:
electromagnetically logging the boreholes to determine electrical parameters of the
hydrocarbon-bearing rock and the at least one overburden layer;
and wherein determining electrical parameters of the hydrocarbon-bearing rock
comprises analysis of data from the step of electromagnetically logging and data
30 from studies of core samples at a plurality of temperatures to determine
temperature dependence of the electrical parameters.

4. The method of claim 1 further comprising determining electrical characteristics of at least one underlying layer.

5. The method of claim 1 further comprising observing the formation for changes in the electrical parameters of the hydrocarbon-bearing rock, and when changes occur in the electrical parameters adjusting a parameter selected from the group consisting of a phase shift between two couplers, a frequency of the radio frequency energy, a parameter of the impedance matching circuitry, and a dimension of the radio frequency coupling apparatus in response thereto.

6. The method of claim 5 further comprising adjusting parameters of the computer model to match the changed electrical parameters and re-simulating to verify continued confinement of applied radio frequency energy within the hydrocarbon-bearing rock.

7. The method of claim 1 wherein there is a second radio frequency coupling apparatus in a second borehole in the hydrocarbon-bearing rock, and wherein the radio frequency energy applied to the second radio frequency coupling apparatus is applied at a phase offset from a phase of the radio frequency energy applied to the first radio frequency coupling apparatus; the phase offset determined to direct radio frequency energy towards a production zone of the hydrocarbon-bearing rock.

8. The method of claim 7, wherein the phase offset is also determined to direct controlling wave direction to direct the radio frequency energy away from a freeze wall.

9. The method of claim 1, wherein the first radio frequency coupling apparatus comprises a first and a second dipole coupling element, and wherein the first and the second dipole coupling element are driven to produce a pattern of radiation into the hydrocarbon-bearing rock that is vertically narrower than a pattern produced by a dipole such that electromagnetic radiation strikes the boundary between the hydrocarbon-bearing rock and the layer of overburden primarily at an angle where it will be reflected back into the formation.

10. The method of claim 1, wherein the first radio frequency coupling apparatus comprises a radiator rod coupled to the center conductor of a coaxial

transmission line, and a plurality of radial groundplane rods coupled to the outer conductor of the coaxial transmission line.

11. A system for extracting marketable hydrocarbons from a carboniferous formation covered by an overburden layer, comprising:

5 at least one radio frequency source;

at least one coupler for coupling radio frequency energy from the radio frequency source into a heated zone of the carboniferous formation;

wherein the radio frequency source operates at a frequency chosen to provide deep penetration of radio frequency energy into the carboniferous formation and
10 chosen such that a high percentage of radio frequency energy striking a boundary between the carboniferous formation and the overburden layer is reflected back into the carboniferous formation.

12. The system of claim 11 wherein the frequency is further chosen by: determining electrical properties of the carboniferous formation at various temperatures;

15 using the electrical properties of the carboniferous formation in a cole-cole model of absorption to model penetration of the radio frequency energy into the carboniferous formation, and choosing the frequency such that adequate penetration is obtained.

13 The system of claim 12, wherein the frequency is further chosen by:

20 determining electrical properties of the overburden layer;

using the electrical properties of the overburden layer and the carboniferous formation in a model of a boundary of the overburden layer and the carboniferous formation, the model of the boundary modeling the boundary as a rough-walled waveguide and being used to choose a frequency where a majority of radio frequency energy from the
25 carboniferous formation that strikes the boundary is reflected back into the carboniferous formation.

14. The system of claim 11, wherein the coupler comprises a plurality of groundplane rods driven radially outwards into a boundary between the overburden layer and the carboniferous formation, and a coupling rod.

30 15. The system of claim 11, wherein the coupler comprises a colinear plurality of center-fed, half-wave, dipoles.

16. The system of claim 11, further comprising a freeze-wall surrounding the heated zone of the carboniferous formation.

17. The system of claim 16, wherein there are a plurality of couplers and wherein a first coupler of the plurality of couplers is driven with radio frequency energy
5 at a phase offset from a second coupler of the plurality of couplers to direct radio frequency energy into a heated zone and away from the freeze wall.

18. The system of claim 11, further comprising means for selectively allocating power from the RF source to a plurality of discrete zones in the carboniferous formation.

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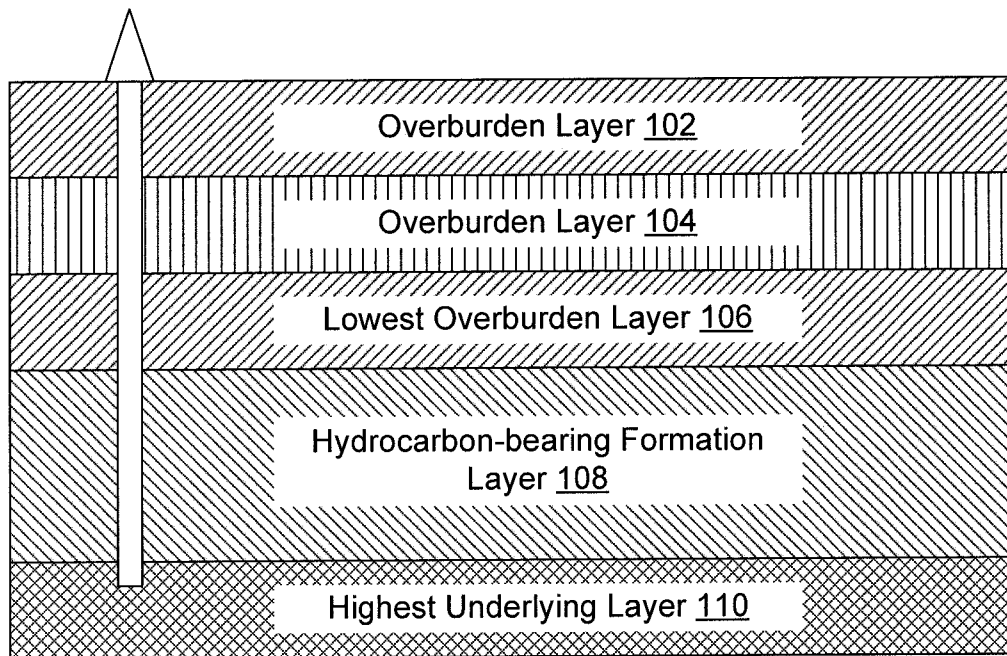


FIG. 1

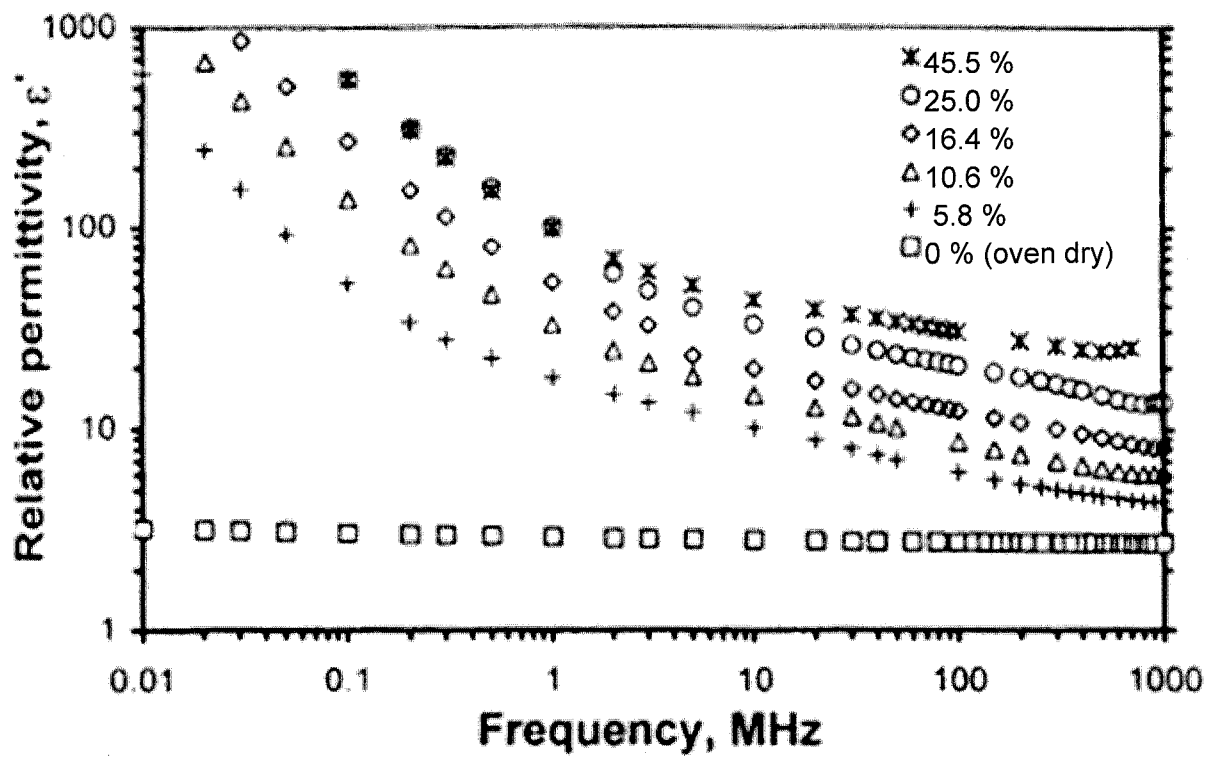


FIG. 2

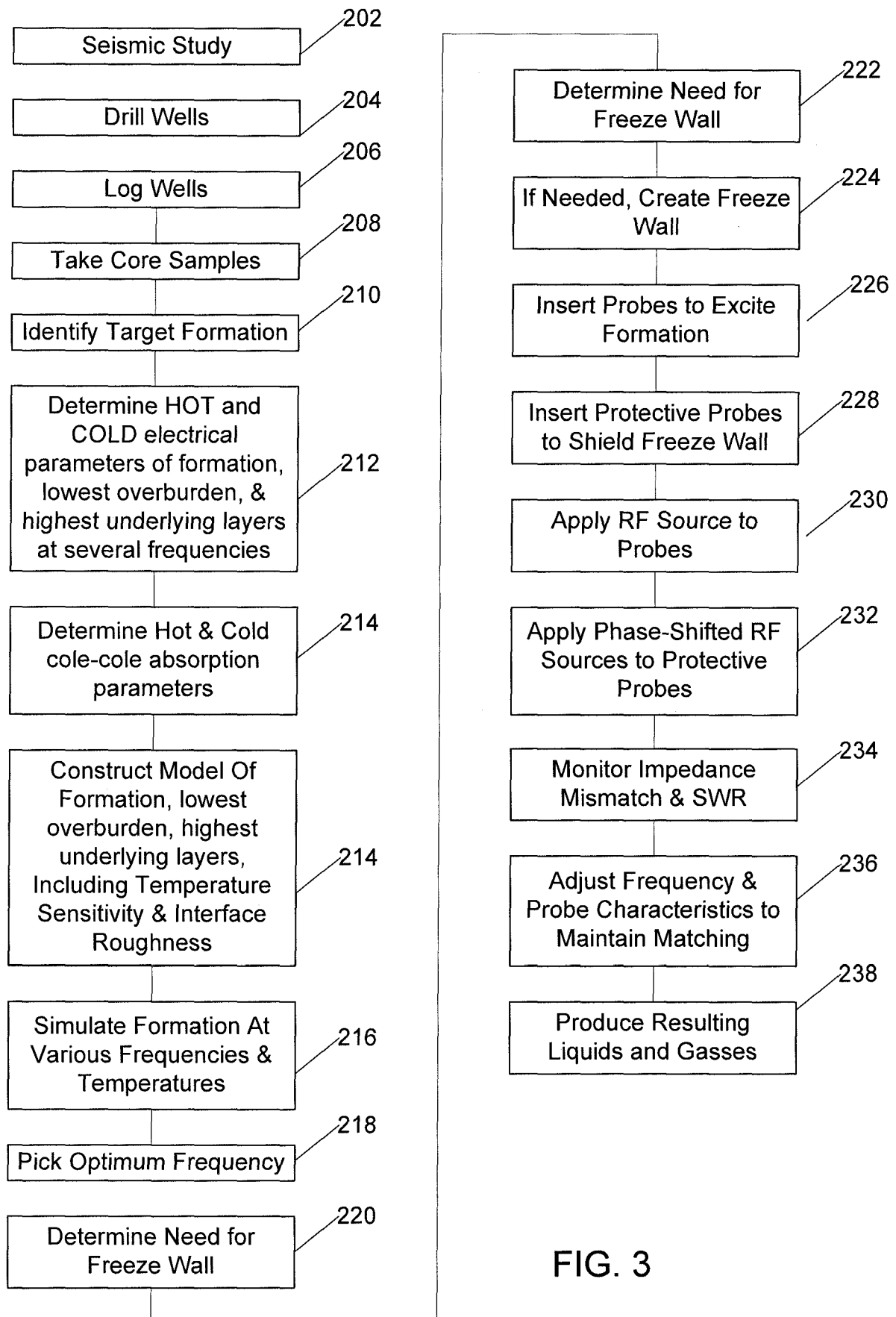


FIG. 3

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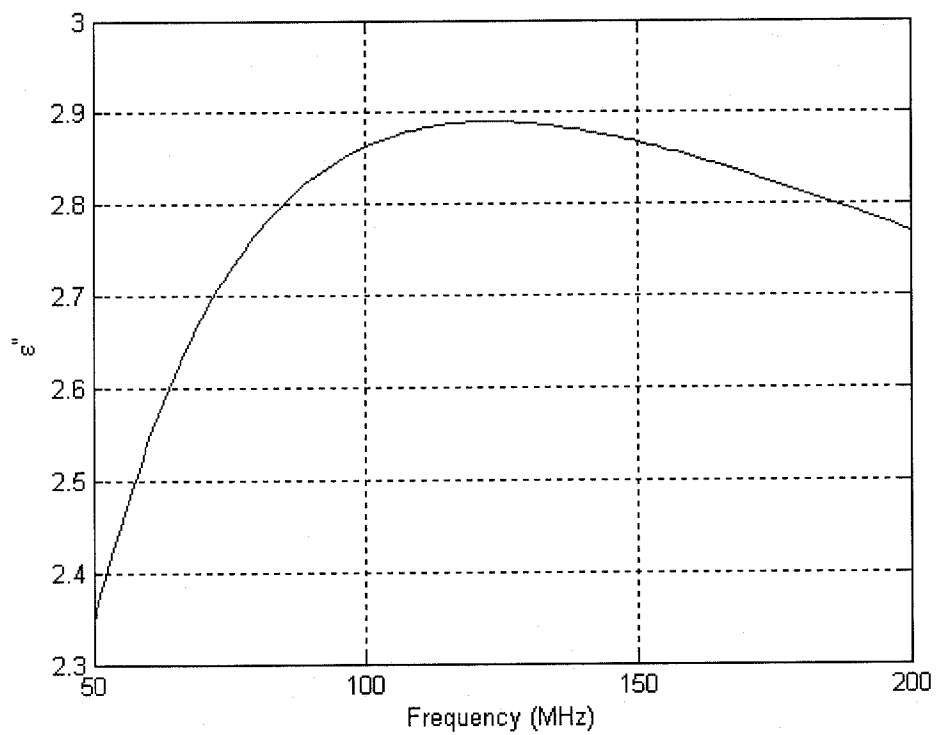


FIG. 4

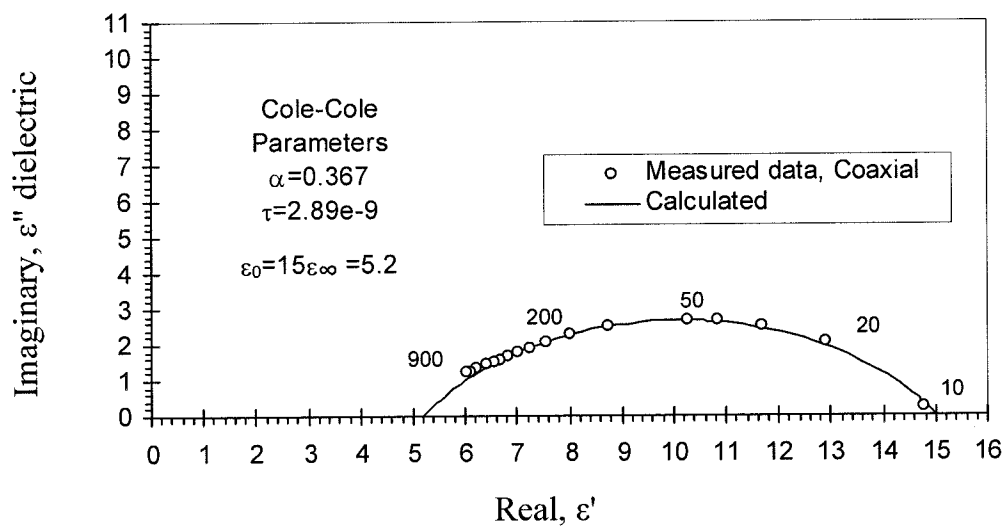


FIG. 5

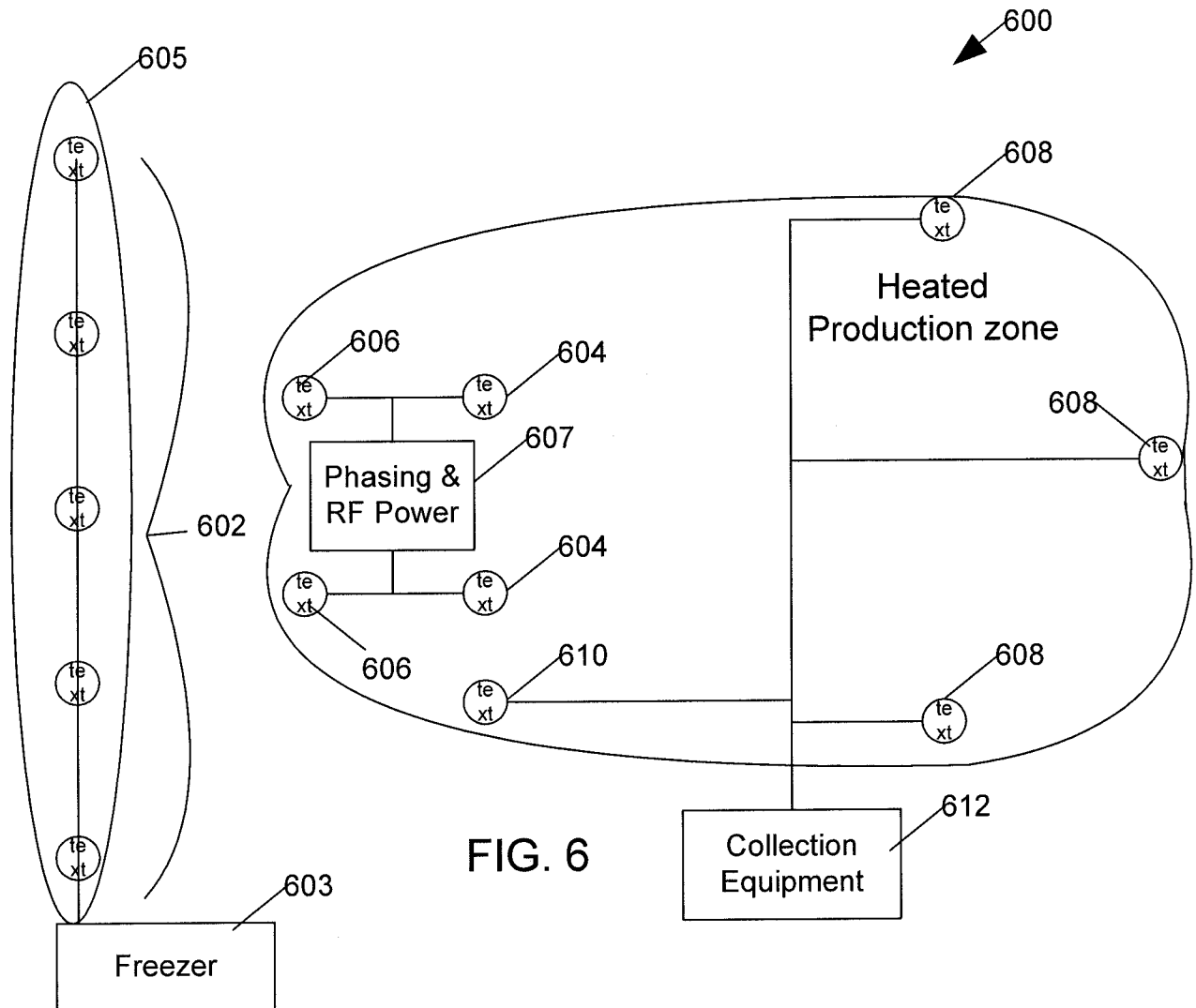


FIG. 6

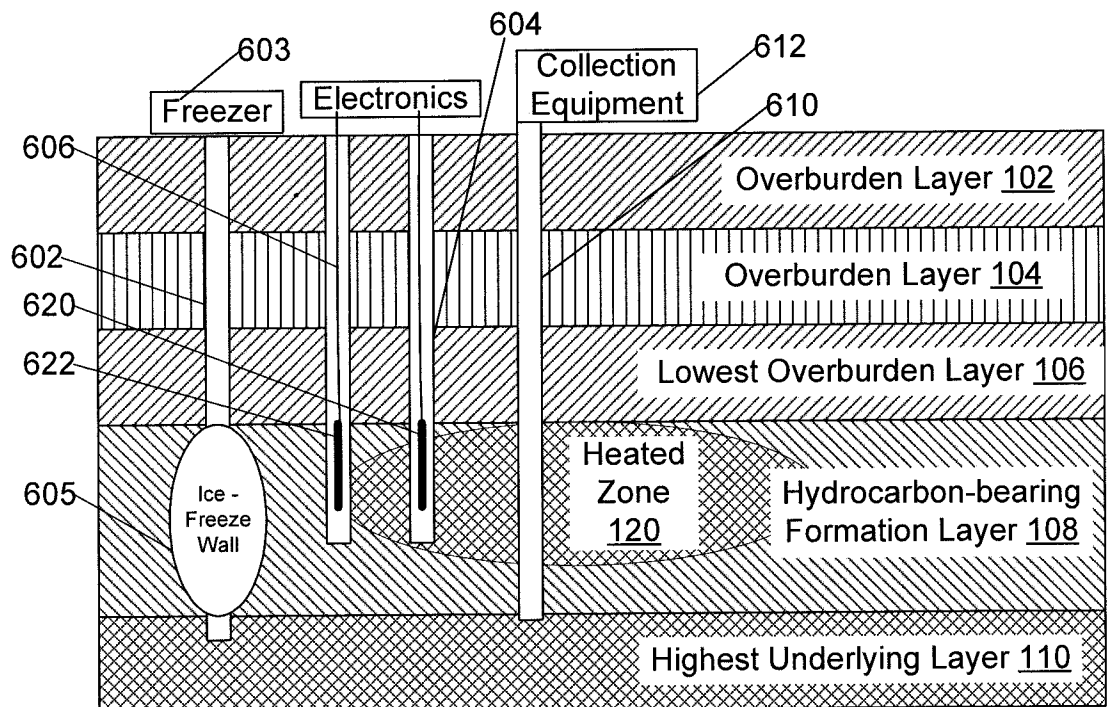


FIG. 7

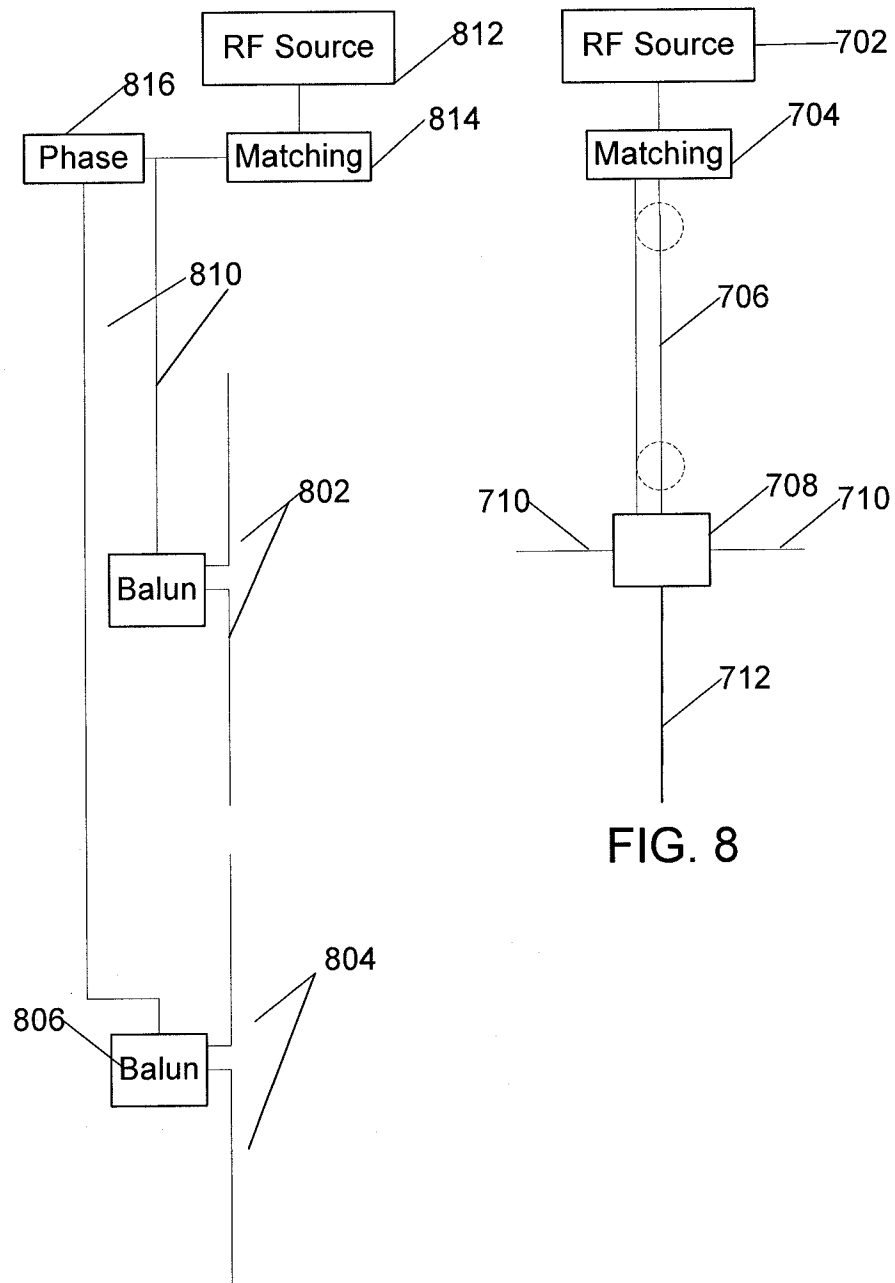


FIG. 8

FIG. 9

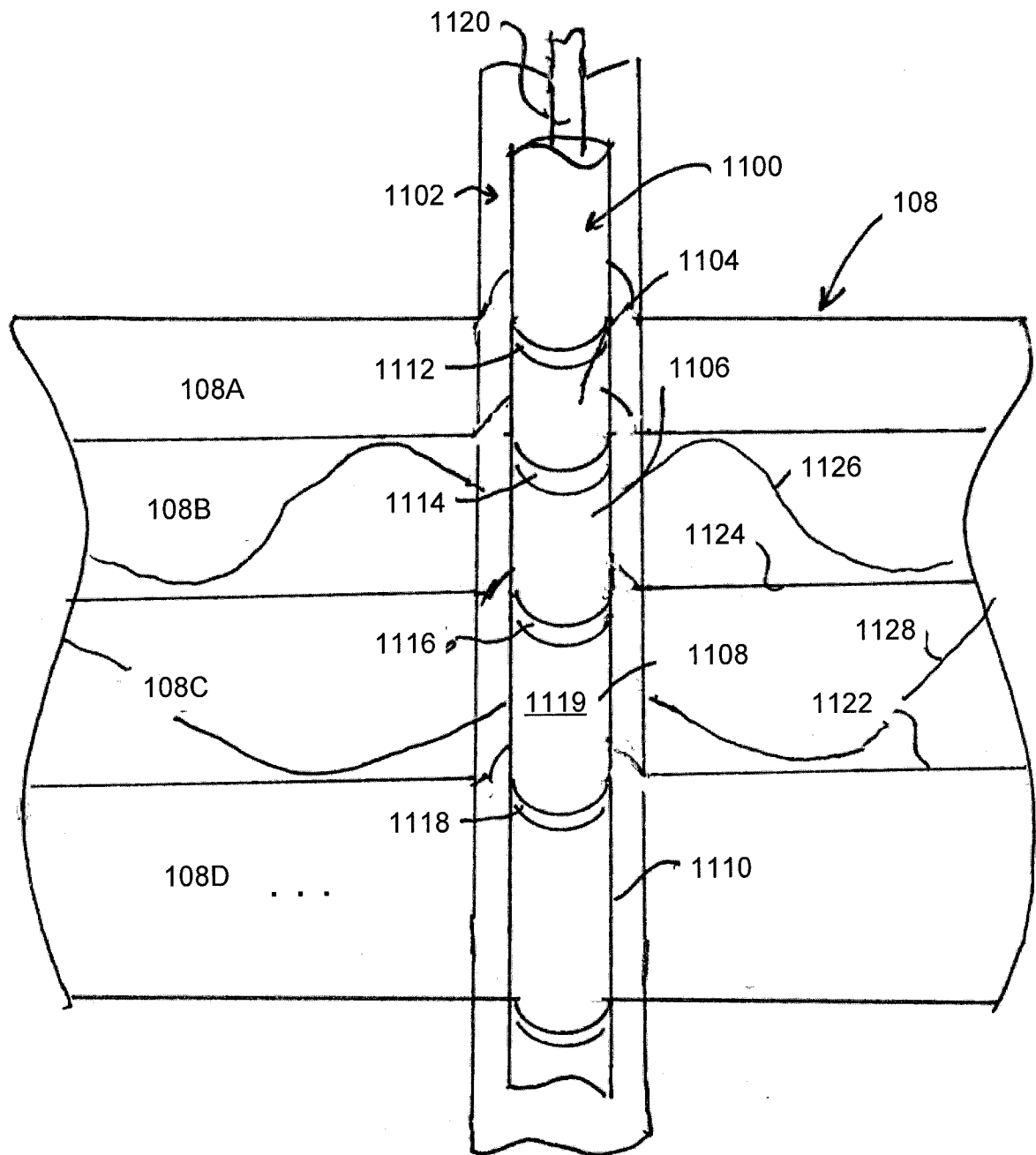


FIG. 10

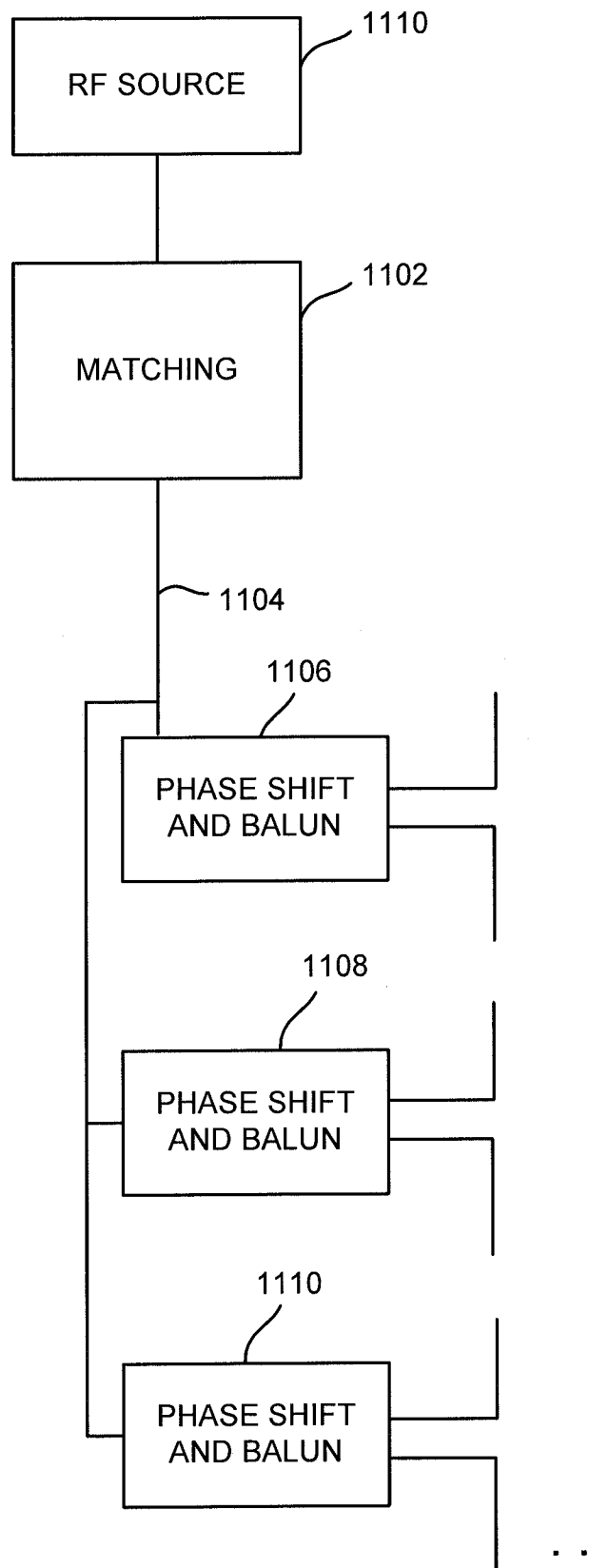


FIG. 11

