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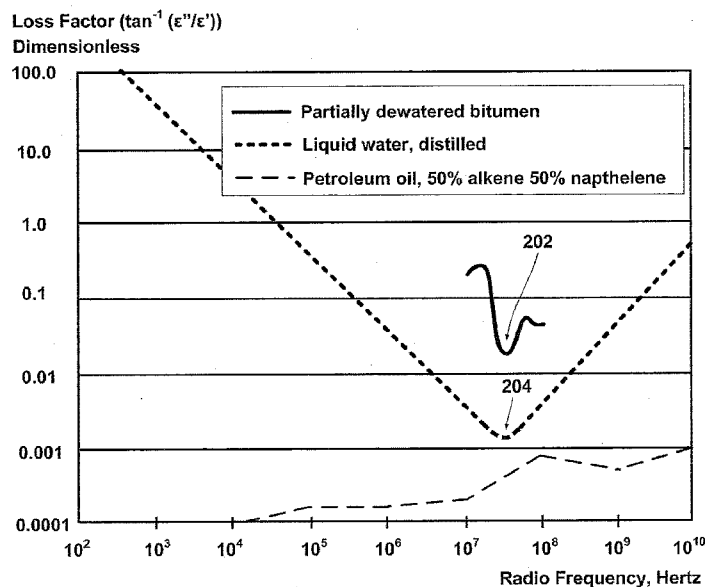
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(54) Title: HYDROCARBON PROCESSING BY USING RADIOFREQUENCY ELECTROMAGNETIC WAVES

**Figure 7**

(57) **Abstract:** An aspect of at least one embodiment of the present invention is a device for cracking heavy hydrocarbons. A linear applicator is positioned within heavy oil containing aromatic molecules. A radio frequency electrical current source is electrically connected to the applicator at a first connection point and a second connection point to create a closed electrical loop. The radio frequency source is configured to apply a signal to the applicator that is sufficient to create a magnetic field and an electric field relative to the axis of the linear applicator. The device also includes a chamber positioned around the applicator generally between the first connection point and the second connection point to concentrate the magnetic field within a region surrounding the applicator and containing the heavy hydrocarbons.

HYDROCARBON PROCESSING BY USING RADIOFREQUENCY ELECTROMAGNETIC WAVES

The present invention relates to using electromagnetic fields and in particular radio frequency electric and magnetic fields to crack or upgrade heavy hydrocarbons. Upgrading heavy hydrocarbons aids in the extraction and processing of hydrocarbons into valuable fuels. In particular, the present invention relates to an advantageous radio frequency (RF) applicator and method that can be used to crack heavy hydrocarbons. The invention breaks the usually unreactive carbon-carbon (C-C) bonds of aromatic molecules, which can be used to upgrade bitumen, reduce the aromatic content of gasoline, or assist in petrochemical synthesis.

As the world's standard crude oil reserves are depleted, and the continued demand for oil causes oil prices to rise, oil producers are attempting to process hydrocarbons from bituminous ore, oil sands, tar sands, oil shale, and heavy oil deposits. These materials are often found in naturally occurring mixtures of sand or clay. Because of the extremely high viscosity of bituminous ore, oil sands, oil shale, tar sands, and heavy oil (heavy hydrocarbons for short), the drilling and refinement methods used in extracting standard crude oil are typically not available. Enhanced oil recovery (EOR) processes are required.

Current EOR technology heats the hydrocarbon formations through the use of steam and sometimes through the use of RF energy to heat or preheat the formation. Steam has been used to provide heat in-situ, such as through a steam assisted gravity drainage (SAGD) system. Steam enhanced oil recovery may not be suitable for permafrost regions due to surface melting, in stratified and thin pay reservoirs with rock layers, and where there is insufficient caprock. At well start up, for example, the initiation of the steam convection may be slow and unreliable as conducted heating in hydrocarbon ores is slow. Water resources may be insufficient to make steam.

RF heating methods use connate in situ water, such as pore water, which is generally present in a hydrocarbon formation. Water is easily heated by electromagnetic fields, so an underground antenna can heat hydrocarbon formations.

The electromagnetically heated pore water conductively heats the hydrocarbons. Because electric and magnetic fields travel near the speed of light, RF heating provides greatly increased speed and penetration through conduction and convection. RF energy can also penetrate impermeable rocks to heat beyond. A radio frequency
5 electromagnetic means to crack and upgrade oil in situ is valuable, especially if accompanied by well stimulation.

Heavy hydrocarbons, such as crude oil and bitumen, often contain aromatic molecules, which make the oil thick and heavy, , and thus difficult to extract. Aromatic molecules are molecules, such as benzene, where the atoms are joined
10 together in a ring shape. Breaking the aromatic rings, which is also known as cracking, creates lighter and thus easier to extract polar hydrocarbon molecules. This process is known as “upgrading” the oil. Aromatic molecules are exceptionally stable molecules and are therefore very difficult to crack. Thus, using radio frequency magnetic fields to crack aromatic molecules can be advantageous.

15 RF electromagnetic (EM) fields can interact strongly with some molecules and weakly with others. In a mixture of molecules, RF EM heating can increase the kinetic energy of one type of molecule without increasing the kinetic energy of other molecule types, which results in selective heating. Thus, high localized temperatures can be achieved without excessively heating a material in bulk.
20 Temperature plays an important role in determining the rate and extent to which chemical reactions occur. Thus, RF EM fields can be effective to cause reactions involving hydrocarbon molecules.

Gasoline is the ubiquitous fuel for automotive transportation. The United States used 140 billion gallons in 2005. In order to meet this demand, modern
25 gasoline is a blend of hydrocarbon molecules typically ranging from 4 to 12 carbons (C_4 to C_{12}). Many types of gasoline molecules, such as aromatic molecules, are hazardous substances that are regulated in the United States and elsewhere. While aromatic molecules are beneficial for high octane (benzene has an octane value of 101), they are released in engine exhaust and evaporated when the gas is pumped.

Thus, gasoline formulation includes tradeoffs in choosing the hydrocarbon molecular species, the emissions level, and the toxicity level of those emissions.

Benzene has been identified as a toxic air pollutant and a potent carcinogen in the US Clean Air Act of 1990. Measured amounts of benzene in
5 polluted city atmospheres are known to cause leukemia, lung, and skin cancer. In view of such severe health effects, the United States Environmental Protection Agency enacted regulations that will lower the benzene content in gasoline to 0.62% in 2011 ("Control of Hazardous Air Pollutants From Mobile Sources", U.S. Environmental Protection Agency, 2006-03-29. p.15853 (<http://www.epa.gov/EPA-AIR/2006/March/Day-29/a2315b.htm>)). Removing aromatics from gasoline reduces
10 toxic emissions which in turn reduces the incidence of leukemia and other cancers. Technologies to reduce benzene levels are needed.

Modern gasoline is a product of varying refinery processes. The Fluid Catalytic Cracking Unit (FCCU) is an example of a process that breaks large high
15 boiling range hydrocarbons into gasoline range products. FCCU output may contain 30 percent aromatics. In a typical FCCU, aromatics like benzene may undergo little cracking. Catalytic Naptha Reforming Units (CNRU) convert saturated low octane hydrocarbons into higher octane products containing 60 percent or more aromatics. Therefore, in a CNRU toxic aromatics are in fact created, especially so if C₆ is
20 included in the feedstock. Methods to adjust FCCU and CNRU output aromatic levels can be advantageous.

Steam cracking is a process in which heavier hydrocarbons are mixed with water and heated to high temperatures such as 900°C to break down heavier hydrocarbons into smaller, lighter hydrocarbons. In steam cracking radical addition
25 may occur to form new aromatic molecules, yet it may be desired to not form aromatic molecules. A steam cracking process that does not produce aromatics can be advantageous.

US Patent, to 6,303,021 to Winter et. al., and entitled "Apparatus and Process For Improved Aromatic Extraction From Gasoline" describes a glycol solvent
30 based process for separating gasoline aromatics that includes contacting the feedstock

with solvent vapors. Means to actually crack the aromatic molecules are not provided.

The present invention is a device for cracking hydrocarbons including heavy hydrocarbons. A linear applicator is positioned within heavy hydrocarbons containing aromatic molecules. A radio frequency electrical current source is electrically connected to the applicator at a first connection point and a spaced second connection point to create a closed electrical loop. The radio frequency source is configured to apply a signal to the applicator sufficient to create a magnetic field and electric field relative to the axis of the linear applicator. The device can also include a chamber positioned around the applicator generally between the first connection point and the second connection point to concentrate the magnetic field within a region surrounding the applicator and to contain the heavy hydrocarbons.

Another embodiment of the present invention provides a circular applicator positioned within heavy hydrocarbons containing aromatic molecules. A radio frequency electrical current source is electrically connected to the circular applicator. The radio frequency source is configured to apply a signal to the applicator that is sufficient to create electric and magnetic fields that are generally present inside the circular applicator, and thus concentrated within a region containing the heavy hydrocarbons.

Another aspect of the present invention is a method for preheating heavy hydrocarbons. An applicator is placed into already extracted heavy hydrocarbons including aromatic molecules. A radio frequency electrical current is applied to the linear applicator sufficient to create an electric and magnetic field relative to the applicator. Aromatic molecules are cracked resulting in lighter polar molecules. The cracked hydrocarbons are then separated from water and sand and other materials. The hydrocarbons are then processed into fuels.

Another aspect of the present invention is a method for upgrading heavy hydrocarbons. The heavy hydrocarbons are separated from water, sand, and optionally other materials. An applicator is placed into the heavy hydrocarbons. The applicator is operated as the hydrocarbons are hydrogenated. A radio frequency

electric current is applied to the applicator sufficient to create a magnetic and electric field relative to the applicator while hydrogen or natural gas are added to the hydrocarbons to produce synthetic crude oil. The hydrocarbons are then processed into fuels.

5 Another aspect of the present invention is a method for extracting heavy hydrocarbons. An applicator is installed into the ore region of a hydrocarbon formation containing aromatic molecules. A radio frequency electric current is applied to the applicator sufficient to create a magnetic and electric field relative to the applicator. The aromatic molecules are cracked into lighter polar molecules. The
10 polar molecules are then removed from the geologic formation.

Other aspects of the invention will be apparent from this disclosure.

Figure 1 is a diagrammatic perspective view of an embodiment of a linear applicator.

Figure 2 is a diagrammatic perspective view of an embodiment of a
15 linear applicator including specific parts of a radio frequency electric current source.

Figure 3 is a diagrammatic perspective view of an embodiment of a circular applicator.

Figure 4 is a flow diagram illustrating a method for pretreating heavy hydrocarbons

20 Figure 5 is a flow diagram illustrating a method for upgrading heavy hydrocarbons.

Figure 6 is a flow diagram illustrating a method for extracting heavy hydrocarbons.

25 Figure 7 is a plot of the radio frequency response of pure water and petroleum oil.

Figure 8 is a plot of the relative dielectric constants of a liquid bitumen (dilbit).

The subject matter of this disclosure will now be described more fully, and one or more embodiments of the invention are shown. This invention may,
30 however, be embodied in many different forms and 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.

Figure 1 shows a diagrammatic representation of a linear applicator (also known as a divergence antenna) that can be used to crack aromatic molecules into polar molecules. The device generally indicated at 10 can be used in situ in a hydrocarbon formation but can also be used to crack heavy oil at an upgrader refinery or other location or to reduce aromatics in gasoline. The device 10 includes a radio frequency electrical current source 12, a linear applicator 14, and a chamber 16.

The radio frequency current source 12 is electrically connected to the linear applicator 14 at a first connection point 13 and a second connection point 15, spaced from the first connection point 13, thereby creating a closed electrical loop. In practice, the catalyst effect of radio frequency electromagnetic fields is not limited to one specific frequency, so a range of frequencies can be used to crack the aromatic molecules into polar molecules. Frequencies between about 0.001 and 100 MHz can be effective to crack aromatic molecules. More particularly, frequencies between about 6.7 MHz and 40.7 MHz can be effective to crack aromatic molecules. For example, in field testing, a frequency of 6.78 MHz was applied to effectively crack aromatic molecules. The use of the water antiresonance frequency, which is about 30 MHz, can also be effective and operation near the water antiresonance is contemplated to minimize energy requirements and cost. The invention advantageously operates with electromagnetic near fields at relatively low frequencies to provide sufficient depth of penetration for large underground formations or industrial above-ground feedstock.

The length of the linear applicator 14 is preferentially short relative the radio wavelength; that is, $L \ll c / (f \sqrt{\epsilon_r})$ where L is the length of the linear applicator 14 in the hydrocarbon mixture, c is the speed of light, f is the radio frequency in hertz, and ϵ_r is the relative dielectric constant of the hydrocarbon mixture. For example, at 6.78 MHz the free space wavelength is about 44 meters and Athabasca oil sand can have a permittivity of about 6, so for these conditions, the linear applicator 14 can be about 4 meters in length. Multiple linear applicators 14 can be used to cover longer

distances. For example, an array of linear applicators 14 may be placed end to end or otherwise. A linear applicator 14 generally functions as a transducer of electric and magnetic near fields.

The radio frequency current source 12 can include a transmitter 22 and
5 an impedance matching coupler 24. The coupler 24 can be selected from numerous devices such as transformers, resonating capacitors, inductors, and other known components to conjugate, match, and manage the dynamic impedance changes of the ore load as it heats. The transmitter 22 can also be an electromechanical device such as a multiple pole alternator or a variable reluctance alternator with a slotted rotor that
10 modulates coupling between two inductors. The RF source 12 may also be a vacuum tube device, such as an Eimac 8974/X-2159 power tetrode or an array of solid state devices. Thus, there are many options to realize the RF source 12.

In a configuration shown in Figure 2, the radio frequency current source includes a transmitter 22, a transformer indicated generally as 24 with a
15 primary ring 26 and a secondary ring 28, and a tuning capacitor 29. The primary ring 24 and the secondary ring 26 can be, for example, copper tubing. The transmitter 22 is electrically connected to the primary ring 26 through a coaxial cable 23. The primary ring 26 can be adjusted, for example, by turning it at an angle relative to the secondary ring 28, which changes the load resistance that the transmitter 22 sees. The
20 tuning capacitor 29 is electrically connected to the secondary ring 26, which allows precision adjustments to the transformer 24 resonance. In field testing, a 10 to 1000 picofarad variable capacitor was adjusted to about 90 picofarads to adjust the transformer resonance to 6.78 Megahertz. The secondary ring 26 is attached to the linear applicator 14 at the first connection point 13 and the second connection point
25 15.

The linear applicator 14 can be any linear conductor, for example, a metal rod or litz cable. Optionally, the linear applicator 14 can be electrically insulated on its surface, for example, with polyimide or Teflon. In certain embodiments, the linear applicator 14 can be a conductive well pipe positioned within
30 the ore region of a hydrocarbon formation. The conductive well pipe can be a typical

steel well pipe or can be coated with copper or another conductive metal. The linear applicator 14 is positioned within ore containing aromatic molecules. For example, the linear applicator 14 can be positioned in situ within an ore region of a hydrocarbon formation. Alternatively, the linear applicator 14 can be located in a refinery or other location and used to crack heavy hydrocarbons that have already been extracted. The linear applicator 14 can also be placed at a gas tank to reduce the aromatic content of gasoline.

A chamber 16 surrounds the linear applicator 14 generally between the first connection point 13 and the second connection point 15. Chamber 16 can function as an oil sand separation cell or cyclone separator by including an inlet 122 and an outlet 126. The chamber 16 can be comprised of any electrically conductive or nonconductive material including, for example, steel, plastic, fiberglass, polyimide, or asphalt cement. When a conductive chamber 16 is used, feedthrough insulators (not pictured) are included to allow the RF electrical currents to follow the applicator into the chamber. Within the chamber 16 are hydrocarbons 17 including aromatic molecules 18. Water molecules 120 can be present or provided. A caustic alkali such as sodium hydroxide can be provided as a surfactant.

Pressurized air 124 can be supplied to the chamber 16 to pressure drive the warmed bitumen from connate sand. The cracked and upgraded hydrocarbons 128 can be drained through the outlet 126. A batch or a continuous process can be realized in the chamber 16. Additional chamber 16 ports (not shown) can supply process water, caustic alkali, salt, or other materials.

When the applicator 10 is operated, current I flows through the linear applicator 14, which creates electric and magnetic near fields in the hydrocarbon 17. The flux lines of the circular magnetic induction field H curl around the applicator 14 while expanding outward radially. The operative mechanism is Ampere's Circuital Law:

$$\oint \mathbf{B} \cdot d\mathbf{l}$$

to form the magnetic near field. The applicator 14 also produces electric near fields which operate from Gauss' Law:

$$\nabla \cdot D$$

(in which the symbol on the left is a del operator). With further derivation, in free space the electromagnetic near fields produced the linear applicator 14 are exactly:

$$E_r = -j\eta (I_0 L e^{-jkr} / 2\pi k r^3) \cos \theta$$

$$E_\theta = -j\eta (I_0 L e^{-jkr} / 4\pi k r^3) \sin \theta$$

$$5 \quad H_\phi = -j\eta (I_0 L e^{-jkr} / 4\pi k r^2) \sin \theta$$

$$E_\phi = H_r = H_\theta = 0$$

Where:

E_r = the radial electric near field

E_θ = the circular electric near field

10 H_ϕ = the circular magnetic near field (induction field)

$-j$ = the complex operator = $\sqrt{-1}$

I_0 = the electric current flowing in the linear applicator 14, uniform distribution assumed

L = the length of the linear applicator 14

15 e^{-jkr} = the time harmonic excitation (AC sinusoidal current is assumed)

k = the wave number = $2\pi/\lambda$

r = the radial distance measured from the center of the linear applicator 14

θ = the angle measured from the axis of the linear applicator 14 (parallel to the linear applicator 14 is 0 degrees, normal to the linear applicator 14 is 90

20 degrees)

Both electric and magnetic near fields are generated by the applicator 14. The fields are rotationally symmetric around the applicator 14. When moist hydrocarbons (hydrocarbons containing water) surround the applicator 14, the electric and magnetic fields are modified from the free space proportions, although the geometry of the produced electric and magnetic near fields E_r , E_θ and H_ϕ are the same.

Hand computation of the linear applicator 14 near field amplitudes in hydrocarbons may be neither practical nor desirable, so a computer method may be preferred. One such method is the method of moments software known as the Numerical Electromagnetic Code (NEC4.1) by Lawrence Livermore National

Laboratories (700 East Ave., Livermore CA 94550). This analysis software has been used to accurately calculate the electric and magnetic near fields of the linear applicator 14 in hydrocarbons. When the using the NEC4.1 software it is important to invoke the Sommerfeld-Norton routine (GN line -1) for real earth.

5 In the NEC4.1, code the applicator structure 14 geometry is emulated by a wire mesh and the electromagnetic properties of the hydrocarbon are input using the relative dielectric constant ϵ_r'' and the electrical conductivity σ . For instance, a rich Athabasca oil sand at 6.78 MHz may be about $\epsilon_r'' = 6$ and $\sigma = 0.002$ mhos/meter. The linear applicator 14 transduces both electric near fields and magnetic near fields
10 in the hydrocarbon 17, and the distribution of those fields can be mapped precisely.

 The linear applicator 14 primarily operates through near fields rather than far fields. As such, the linear applicator 14 does not have to produce radio waves to be effective. An advantage is that it is not necessary to have a cavity or a standoff distance between the applicator 14 and the hydrocarbon 17, which would be costly to
15 create. The linear applicator 14 can be immersed directly in underground formations and operated while in contact with hydrocarbons. Above ground, the applicator 14 may be directly in contact with a hydrocarbon feedstock as well, although a standoff distance between the hydrocarbon material and the linear applicator 14 can be used if desired. The applicator 14 is effective at lower rather than higher radio frequencies,
20 which provides the operative advantage of increased power and penetration. It can be advantageous to generate alternating electrical energy at lower rather than higher frequencies for reasons of efficiency.

 Operation at hydrocarbon molecule resonance frequencies is not required, although they can be used if desired. The magnetic and electric near fields
25 about the linear applicator 14 interact with the various species of molecules in moist hydrocarbons. Electric near fields can increase the kinetic energy of water molecules, and they can excite the dielectric moments of the hydrocarbon molecules themselves, which can cause cracking and upgrading of the hydrocarbons. Magnetic near fields can induction heat the water molecules by creating eddy electric currents that heat by
30 joule effect. The magnetic fields can create eddy electric currents in the aromatic

molecule rings. Adding small amounts of water to the hydrocarbon feedstock or underground ore prior to exposing the hydrocarbons to electromagnetic fields can thus be advantageous. RF and moist hydrocarbons provide in effect a low bulk temperature steam cracking process.

5 Aromatic molecules are both conductive loops and planar molecules. It is contemplated that magnetic fields break the aromatic molecules because the aromatic molecules have an inductive like relationship to the linear applicator 14. In other words, the linear applicator 14 is akin to a transformer primary winding, and the aromatic molecules are akin to a transformer secondary winding. The work function
10 of moving the electrons around the aromatic molecules can break the aromatic molecules and the aromatic ring current can be induced in the π electrons. It is further contemplated that the planar aromatic molecules can reorient their planes normal to the magnetic field flux lines, and this orientation causes the polycyclic aromatic molecules to crack as they break their attachments to other rings. Both the electric
15 and magnetic fields may interact with small amounts of water present in the hydrocarbon stock to create radicals, especially the hydroxyl radical OH $\cdot$, which can help initiate upgrading.

 It is contemplated that the linear applicator 14 does not behave significantly as an electrode, even when uninsulated and in direct contact with moist
20 hydrocarbons. In other words, the linear applicator 14 does not significantly feed electrons into the hydrocarbon stock by conductive contact. This is because the linear applicator 14 provides a highly electrically conductive path relative to the more resistive hydrocarbon material, so nearly all of the electric current follows the linear applicator 14 path. This is an advantage as it enhances process reliability. Electrode
25 systems in hydrocarbons can be unreliable due to asphaltine deposition on the electrode (especially with live oils), water boil off at the electrodes, or coking. Thus, the advantages of the linear applicator 14 can include one or more of the following: it is reliable, not limited as to power, and it does not require water flooding or other means to maintain electrical contact with the hydrocarbons. The linear applicator 14

achieves indirect electrical contact with hydrocarbon mixtures by magnetic field induction and electric field displacement.

Figure 3 shows a diagrammatic representation of an alternative embodiment, where a circular applicator 30 (also known as a loop or curl antenna) is used to crack heavy oil. The device generally indicated at 30 can be used in situ in a hydrocarbon formation but can also be used to crack heavy oil in a refinery or other location. The device 30 includes a radio frequency electrical current source 32 and a curved applicator 34. A circular applicator 30 produces both electric and magnetic near fields.

The radio frequency electrical current source 32 is the same as or similar to the radio frequency electrical current source 12 in Figure 1. The radio frequency current source 12 is electrically connected to the circular applicator 34 at a first connection point 33 and a second connection point 35, thereby creating a closed electrical loop.

The circular applicator 34 can be any curved conductor, for example, a curved metal rod. The circular applicator 34 is positioned within heavy hydrocarbons containing aromatic molecules. For example, the circular applicator 34 can be positioned in situ within an ore region of a hydrocarbon formation. Alternatively, the circular applicator 34 can be located in a refinery or other location and used to crack heavy hydrocarbons that have already been extracted.

For such an applicator, the magnetic field 36 that forms when the device is operated is concentrated substantially through the center of the circular applicator 34. Therefore, when the device is operated heavy hydrocarbons including aromatic molecules within or nearby the circular applicator 34 can be cracked into lighter polar molecules.

Multiple circular applicators 30 can create zones of uniform magnetic fields. In this arrangement, each circular applicator 30 carries an equal electrical current flowing in the same direction. The circular applicators 30 can be separated by a distance equal to the diameter of each circular applicator 30. While the linear applicator 14 operates on the principle of divergence, the circular applicator 30

operates on the principle of curl. Thus, the line and the circle geometry can both provide the required electric and magnetic near fields. Compound embodiments of the applicators may be also be rendered. A coil of wire can be formed by multiple circular applicators 30 connected in series. Helix, solenoid, and spiral coils are thus contemplated applicator embodiments.

A representative field test will now be described. A linear applicator 14 was used as depicted in Figure 2. The chamber 16 was filled with heavy hydrocarbons including 32.27 percent aromatic molecules and 27.09 percent polar molecules. The radio frequency source 12 was operated at 6.78 Megahertz. After running the device for 18 minutes, the hydrocarbons were analyzed and virtually all of the aromatic molecules had been converted to polar molecules. Present in the oil after processing were 0.96 percent aromatic molecules and 60.92 percent polar molecules. Table 1 details the Field Test Results:

Table 1: Field Test Results		
Parameter	Value	Comment
Objective	Bitumen ore upgrading	
Hydrocarbons 17 / test sample	Rich Athabasca oil sand. By weight, 16 % bitumen, 1.2 % water, remainder sand and clay	Mined near Fort McMurray, Canada
Field Test Result	Near total conversion of aromatic molecule fraction to polar molecules was accomplished	Measured

Test sample relative dielectric permittivity, real component, prior to application of electromagnetic fields	≈ 9 at 6.78 MHz	Measured
Test sample electrical conductivity, prior to application of electromagnetic fields	0.012 mhos/meter at 6.78 MHz	Measured
Test sample density	0.072 pounds/inch ³ (2.0 g/cm ³)	Measured and calculated
Chamber 16 geometry	Polycarbonate plastic tube, 4 inches (10cm) in diameter, 12 inches (30 cm) high	Measured
Test sample volume	150.7 inches ³ (2470 cm ³)	Measured
Test sample weight	10.9 pounds (4.94 Kg.)	Measured
Duration of electromagnetic field exposure	18 minutes	Measured
Initial temperature	20° C	Measured
Ending temperature	86° C	Measured
Test sample aromatic content before test (of the ore's hydrocarbon fraction)	32.27 % by weight	Measured
Test sample polar content before test (of the ore's hydrocarbon fraction)	27.09 % by weight	Measured

Test sample saturate content before test (of the ore's hydrocarbon fraction)	17.23 % by weight	Measured
Test sample asphaltene content before test (of the ore's hydrocarbon fraction)	23.41 % by weight	Measured
Test sample aromatic content after test (of the ore's hydrocarbon fraction)	0.96 % by weight	Measured
Test sample polar content after test (of the ore's hydrocarbon fraction)	60.92 % by weight	Measured
Test sample saturate content after test (of the ore's hydrocarbon fraction)	15.30% by weight	Measured
Test sample asphaltene content after test (of the ore's hydrocarbon fraction)	22.82% by weight	Measured
Test sample temperature before test	30° C	Measured
Test sample temperature after test	82° C	Measured
Radio frequency of electrical current source 12	6.78 MHz	Measured
Linear applicator 14 construction	12 inch (30 cm) long brass rod, 3/8 inch (0.95 cm) OD	Implemented

Transformer 24	Two ring transformer with resonant secondary	
Transformer primary winding diameter	3 feet (0.9 m)	Measured
Transformer secondary winding diameter	5 feet (1.5 m)	Measured
Transformer secondary winding	One turn of ½ inch (1.27 cm) (nominal) copper water pipe	Specified
Transformer primary winding	One turn of ½ inch (1.27 cm) (nominal) copper water pipe	Specified
Secondary winding resonating capacitor	90 picofarads	Measured
H field strength realized in test sample	7 Amps/meter	Calculated
E field strength realized in test sample	420 Volts/meter	Calculated
Electromagnetic field impedance (ratio of E/H in test sample)	60 ohms	Calculated
Induced electric currents in test sample	0.86 amps/meter ²	Calculated
Energy delivered to the test sample	8.5 watt hours per pound of mass (18.7 watt-hours per Kg. of mass)	Calculated

In the control experiment, heating the rich Athabasca oil sand from 30° C to 100° C by conducted heat in a conventional oven did not significantly convert

the aromatic molecules to polar molecules. Therefore, the electric and magnetic fields were essential to initiate the molecular cracking.

The inventors have the following theory to explain the above results. The invention is not limited by the accuracy or applicability of this theory. The radio frequency electric and magnetic fields are akin to a catalyst. The radio frequency electric and magnetic fields raised the vibrational energy of the liquid water molecules in the oil sand relative to the hydrocarbon molecules. In other words, selective heating was realized. The effect was that the bulk heating of the oil sand was minimized while the pore water in oil sand was at high kinetic energy and temperature. The Field Test accomplished a bulk low temperature steam cracking process from pore water. Water in the oil sand can donate radicals, such as the hydroxyl radical OH⁻ to help initiate the cracking and upgrading reaction.

During the test, dry nitrogen was introduced in the inlet 122 to pressurize the test chamber 16. The dry nitrogen provided a gas pressure drive to release the bitumen from the sand, such that water and oil 128 were produced together from the outlet 126 at the bottom of the chamber 16. Thus, the chamber 16 functioned as a separation cell as well as an upgrader. The oil produced at the outlet 126 was sent for chemical analysis. The produced oil was observed to be thinned in viscosity relative to Clark Process bitumen, which means the electric and magnetic fields reduced the API gravity. Some roiling of the oil sand was noted about 10 minutes after the electric and magnetic fields were applied, which indicates the electric and magnetic fields provided the energy to pop the water pores to release oil. The electric and magnetic fields provided a synergy to both separate bitumen from the sand and to upgrade the bitumen at the same time. No coking of the chamber 16 or applicator 14 was noted after the Field Test, which can in some embodiments be an advantage of the present invention over conventional high temperature ($\approx 900^{\circ}\text{C}$) steam cracking processes.

The Field Test delivered 8.53 watt hours of energy per pound of mass (18.76 watt-hours per Kg. of mass) to the oil sand. When aromatic molecules are broken, they become assymmetric and polar (polarized to electric fields). This was

observed in the Field Test data as the decrease in aromatic molecules was accompanied by a corresponding increase in polar molecules.

- 5 The electrical energy cost to treat large volumes of rich Athabasca oil sand will now be considered. Treatment times and RF powers were not optimized in the Field Test described above. An approximation of the minimum amount of electrical energy required to convert the aromatic molecules to polar molecules as shown in Table 2.

Electrical Energy Costs To Treat Hydrocarbon Ore	
Hydrocarbon ore	Rich Athabasca oil sand
Objective	Conversion of greater than 90 % of the aromatics to polar.
Ore specific heat C_p	0.26 BTU/lb•°F (0.43 Watt-hours/°C•kg)
Ore starting temperature	86° F (30° C)
Ore Ending temperature	187° F (86° C)
Ore ΔT	119° F (48° C)
Delivered energy required	24 BTU per pound of ore mass
Delivered energy required	3.2 watt-hours per kg of ore mass
Transmitter efficiency η (RF source 12)	65%
Applicator efficiency (linear applicator 14)	90%
Prime electrical energy required (e.g., 60 Hz)	10.5 watt hours per pound of ore mass (23.2 Watt-hours/kg)
Electrical energy rate (e.g., 60 Hz)	\$0.12 per kilowatt hour
Electrical energy cost (e.g., 60 Hz)	\$2.11 US dollars per ton of ore treated (\$2.33 /1000Kg)

It is anticipated that further optimization will further reduce the electrical energy cost.

Many operating concepts are possible. For example, the invention may include cogeneration to recover the waste heat from an on-site 60 Hz electrical generator. Separated bitumen without sand may be RF treated, such as bitumen previously separated by the Clark Process. The applicator 14 can provide the cracking in situ and underground, where the electric and magnetic near fields also stimulate well production.

Figure 4 depicts a method for pretreating heavy hydrocarbons 40. At the step 41, an applicator is placed into heavy hydrocarbons including aromatic molecules that have already been extracted. In this case, the ore has already been extracted. The ore can be, for example, oil sand, which contains sand and water in addition to the hydrocarbons. The applicator can be, for example, the same or similar to the linear applicator of Figure 1. Alternatively, the applicator can be, for example, the same or similar to the circular applicator of Figure 3 or a coil formed from multiple applicators.

At the step 42, a radio frequency electrical current is applied to the applicator, which is sufficient to create a magnetic field relative to the applicator. For example, a 0.001 to 100 MHz signal can be sufficient to create an electric and a magnetic field relative to the applicator to crack aromatic molecules in the ore. At the step 43, the electric field and the magnetic field formed in the step 42 cracks the aromatic molecules into polar molecules.

At the step 44, the hydrocarbons are separated from water, sand, and other materials present in the hydrocarbons. Known techniques can be used to separate the hydrocarbons from the water and sand. For example, they can be separated using hot water and surfactant in a cyclone separator or primary separation vessel. Alternatively, separating the sand and upgrading the hydrocarbons can occur simultaneously.

At the step 45, the hydrocarbons are processed into fuels. The hydrocarbons from step 44, which now consist of the cracked hydrocarbons (or

hydrocarbons containing polar molecules and few aromatic molecules) go through further processing in order to make fuels. One or more known processing steps can follow. For example, the cracked hydrocarbons can be hydrogenated to by adding hydrogen or natural gas to the hydrocarbons, which results in synthetic crude oil. The
5 synthetic crude oil can then be further processed, for example, by fractionating or catalytic cracking resulting in sour synfuels. Finally, the sour synfuels can be processed through sweetening, which includes sulfur and metal removal. The final result is sweet fuel, such as gasoline, diesel, and JP4.

Figure 5 depicts a method for upgrading heavy oil 50. At the step 51,
10 the hydrocarbons are separated from water and sand present in the ore containing heavy hydrocarbons including aromatics molecules that have already been extracted. Known techniques can be used to separate the hydrocarbons from the water and sand. For example, they can be separated using hot water and surfactant.

At the step 52, an applicator is placed into the heavy hydrocarbons.
15 The applicator can be, for example, the same or similar to the linear applicator of Figure 1. Alternatively, the applicator can be, for example, the same or similar to the circular applicator of Figure 3.

At the step 53, a radio frequency electrical current is applied to the applicator, which is sufficient to create electric and magnetic fields relative to the
20 applicator that can crack the aromatic molecules into polar molecules, and the oil is hydrogenated to create synthetic crude oil.

It is contemplated that an advantage of certain embodiments herein is that the heavy oil can be simultaneously cracked and hydrogenated. The process of hydrogenation includes adding hydrogen or natural gas to the oil, and generally needs
25 activation energy such as heat to complete. In addition to cracking the aromatic molecules into polar molecules, the magnetic fields can heat the oil through resistive and conductive heating.

For example, magnetic near fields (H) surrounding the applicator cause eddy electric currents to form in the hydrocarbons by inductive coupling. The eddy
30 electric currents then heat the ore by resistance heating or joule effect, such that the

heating is a compound process. The applicator is akin to a transformer primary winding and the ore the secondary winding, although windings do not exist in the conventional sense. The magnetic near field mode of heating is reliable as it does not require liquid water contact with the applicator. The electric currents flowing along the applicator surfaces create the magnetic fields, and the magnetic fields curl in circles around the antenna axis. The strength of the heating in the ore due to the magnetic fields and eddy currents is proportional to:

$$P = \pi^2 B^2 d^2 f^2 / 12 \rho D$$

Where:

- 10 P = power delivered to the ore in watts
- B = magnetic flux density generated by the well antenna in Teslas
- D = the diameter of the well pipe antenna in meters
- ρ = the resistivity of the hydrocarbon ore in ohmmeters = $1/\sigma$
- f = the frequency in Hertz
- 15 D = the magnetic permeability of the hydrocarbon ore

The strength of the magnetic flux density B generated by a linear applicator 14 derives from Ampere's law and is given by:

$$B_\phi = \mu I L e^{-jkr} \sin \theta / 4 \pi r^2$$

Where:

- 20 B = magnetic flux density generated by the well antenna in Teslas
- μ = magnetic permeability of the ore
- I = the current along the well antenna in amperes
- L = length of antenna in meters
- e^{-jkr} = Euler's formula for complex analysis = $\cos(kr) + j \sin(kr)$
- 25 θ = the angle measured from the well antenna axis (normal to well is 90 degrees)
- r = the radial distance outwards from the well antenna in meters

In free space, the electromagnetic near fields produced by a circular applicator 30, e.g., a loop or curl antenna are exactly:

$$H_r = a^2 (I_0 L e^{-jkr} / 2r^3) \cos \theta$$

$$H_\theta = a^2 (I_0 L e^{-jkr} / 4r^3) \sin \theta$$

$$E_\phi = -ja^2 (k I_0 e^{-jkr} / 4r^2) \sin \theta$$

$$H_\phi = E_r = E_\theta = 0$$

5 Where:

H_r = the radial magnetic near field

H_θ = the circular magnetic near field

E_ϕ = the circular electric near field

$-j$ = the complex operator = $\sqrt{-1}$

10 A = area inside of the applicator 30

I_0 = the electric current flowing in the circular applicator 30, uniform distribution assumed

L = the length of the circular applicator 30

e^{-jkr} = the time harmonic excitation (AC sinusoidal current is assumed)

15 k = the wave number = $2\pi/\lambda$

r = the radial distance measured from the center of the circular applicator 30

θ = the angle measured from the plane of the circular applicator 30 (normal to the linear applicator 14 is 90°)

The circular applicator 30 produces slightly more magnetic field strength than the
 20 linear applicator 14 while the linear applicator 14 produces slightly more electric field strength. However, the effectiveness of the linear applicator 14 and circular applicator 30 are similar. The linear applicator 14 can be preferred for underground applications and can be comprised of, for example, a well pipe. The circular applicator can be preferred for certain surface applications. Any partially electrically
 25 conductive ore can be heated by application of electric and magnetic fields described herein as long as the resistance of the applicator's electrical conductors (metal pipe, wires) is much less than the ore resistance.

At the step 54, the synthetic crude oils are processed into fuels. One or more known processing steps can follow. The synthetic crude oil can then be further
 30 processed, for example, by fractionating or catalytic cracking resulting in sour

synfuels. Finally, the sour synfuels can be processed through sweetening, which includes sulfur and metal removal. The final result is sweet fuel, such as gasoline, diesel, or JP4.

Figure 6 depicts a method for extracting heavy oil 60. At the step 61, an applicator is positioned into the ore region of a hydrocarbon formation containing heavy hydrocarbons including aromatic molecules. The applicator can be, for example, the same or similar to the linear applicator of Figure 1. Alternatively, the applicator can be, for example, the same or similar to the circular applicator of Figure 3. An advantage of using a linear applicator is that an existing or installed conductive pipe can function as the linear applicator. For example, the linear applicator can be a typical steel well pipe that may or may not be coated in a highly conductive metal, such as copper.

At the step 62, a radio frequency electrical current is applied to the applicator, which is sufficient to create a magnetic field that can crack the aromatic molecules into polar molecules. For example, a 0.001 to 100 MHz signal can be sufficient to create a circular magnetic field relative to the applicator to crack aromatic molecules in the ore. At the step 63, the magnetic field formed in the step 62 cracks the aromatic molecules into polar molecules.

At the step 64, the cracked hydrocarbon molecules are extracted. For example, the lighter polar molecules can flow into an extraction pipe, or pumps or other mechanisms in the formation can pump the oil to the surface.

Figure 7 shows the frequency response of a medium weight hydrocarbon oil. It provides a plot of the loss factor of distilled liquid water, partially dewatered bitumen, and a 50% alkene 50% naphthalene mixture of petroleum oil. Loss factor indicates how much a material will heat when an electromagnetic field is applied to it. Thus, a molecule with a high loss factor will heat more than a material with a low loss factor. There is a minimum at point 202 in the frequency response of the partially dewatered bitumen and there is also a minimum 204 in the frequency response of the distilled liquid water. The two minima 202, 204 coincide in frequency and are near 30 MHz. The minima 202, 204 comprise an antiresonance of the water

fraction. Operating the transmitter 22 at a frequency near the minima 202, 204 antiresonance of water to reduce the kinetic energy of the water molecules in the hydrocarbon stock relative to the kinetic energy of the hydrocarbon molecules can be advantageous.

5 It can also be advantageous to adjust the radio frequency away from the water antiresonance frequency (say below 15 MHz or above 60 MHz) to increase the kinetic energy of water molecules relative to the kinetic energy of hydrocarbon molecules. Thus, it is possible to instantaneously adjust the temperature of water molecules in the mixture relative to the temperature of hydrocarbon molecules by
10 adjusting the radio frequency. Adjusting the temperature of molecules initiates and controls chemical reactions. Varying the radio frequency allows precise control of a low bulk temperature steam cracking process.

 The radio frequency electromagnetic fields provided by the linear applicator 14 and the curl applicator 30 can also control the formation and activity of
15 water spawned radicals. The hydroxyl radical OH $\cdot$ can be formed from water and it reacts quickly with heavy hydrocarbons. Radicals can be formed in the presence of radio frequency electromagnetic fields, especially magnetic fields, which are known to influence the nuclear spins of the paramagnetic water molecules. Radicals (often referred to as free radicals) are atoms, molecules, or ions with unpaired electrons on
20 an open shell configuration. The unpaired electrons cause radicals to be highly chemically reactive. Water can be slightly repelled by magnetic fields (diamagnetism) while radicals are slightly attracted by magnetic fields (paramagnetism). RF electric currents in water are not generally expended through water electrolysis, which commonly occurs when DC electric currents pass through
25 water. This means that the water is not split significantly into hydrogen and oxygen gasses by RF electric currents, so the energy of RF electric currents is available to increase the kinetic energy of the water molecules and to form radicals.

 Figure 8 shows the real and imaginary relative permittivity ϵ_r' and ϵ_r'' for liquid bitumen. It depicts the real and imaginary relative dielectric constants for a
30 dilbit produced in Athabasca Province, Canada. The liquid bitumen included naptha

to reduce viscosity, and it included about 2% water by weight. The effects of the 2% water fraction are quite evident in Figure 8. The 2% water fraction caused a local minimum in the imaginary permittivity (ϵ'') near 30 MHz. This minimum occurred because the frequency response of the hydrocarbon molecules was relatively flat compared to the more variable response of the water. Water reacts strongly to the RF electromagnetic fields at frequencies away from about 30 MHz and less so near 30 MHz. Heavy hydrocarbon molecules can have resonant responses at frequencies near 30 MHz, but the dilbit hydrocarbon response is flat because dilbit contains hydrocarbons of many molecular weights. Thus, the radio frequency may be varied relative 30 MHz to control the reactivity of water in the chemical reaction.

Radio frequency electric and magnetic fields were tested on the Figure 8 dilbit at or near the water antiresonance frequency (27.12 MHz was used) and cracking occurred. The water antiresonance may be useful over a broad range in the present invention, for example, from 0.001 to 100 MHz. Adjusting the radio frequency of the transmitter 22 to vary the reactivity of water relative to the hydrocarbons by tuning frequency toward or away from water antiresonance frequency can be advantageous. Adjusting the frequency of the transmitter 22 near the water antiresonance frequency reduces the kinetic energy and temperature of the water molecules relative to the hydrocarbons. Adjusting the frequency of the transmitter 22 away from the water antiresonance increases the kinetic energy of the water molecules relative to the hydrocarbons. Temperature and activity of the water molecule fraction is adjusted precisely and instantaneously by adjusting the radio frequency of the transmitter 22. The permittivity (ϵ) of a material is a measure of how radio frequency electric fields affect a medium. Thus, in Figure 8 the imaginary component of the relative permittivity (ϵ'') is a good measure of how much a material fraction will radio frequency heat, and it relates to the selective heating and kinetic energy that different molecular species will receive in RF electromagnetic fields.

The preferred radio frequencies, between about 0.001 to 100 MHz, have the advantage of being practical at industrial process scale and power level. The prompt (nearly instantaneous) half power penetration depth of electromagnetic near

fields, both electric and magnetic (E and H) in rich Athabasca oil sand ore at 1 MHz is about 10 meters, and the ultimate penetration depth over time can be extended nearly indefinitely if heating is allowed to progress. Higher and lower radio frequencies can be used to increase or reduce the penetration depth of the electric and magnetic fields to any depth desired. The equation for radio frequency skin depth approximates the electric and magnetic field penetration:

$$\delta = \sqrt{\rho/\omega\mu} \text{ where}$$

δ = the skin depth,

ρ = the resistivity of the hydrocarbon formation or feedstock

10 ω = the angular frequency = $2\pi f$,

and μ = the absolute magnetic permeability which is typically $4\pi \times 10^{-7}$ in hydrocarbon ores. In addition to RF skin depth Lamberts Law also applies, e.g., the electromagnetic fields weaken with distance due to geometric spreading.

The addition of sodium chloride (salt, NaCl) to the hydrocarbon feedstock or underground ore modifies solution ion content, electrical conductivity, and imaginary permittivity. The addition of a caustic alkali, such as sodium hydroxide (NaOH) or sodium carbonate (Na_2CO_3) to the process feedstock or underground ore can also be useful: caustic alkali has the synergy and operative advantage of increasing the imaginary dielectric constant of the water in the feedstock relative to the dielectric constant of the hydrocarbons. The caustic alkali may also provide a surfactant.

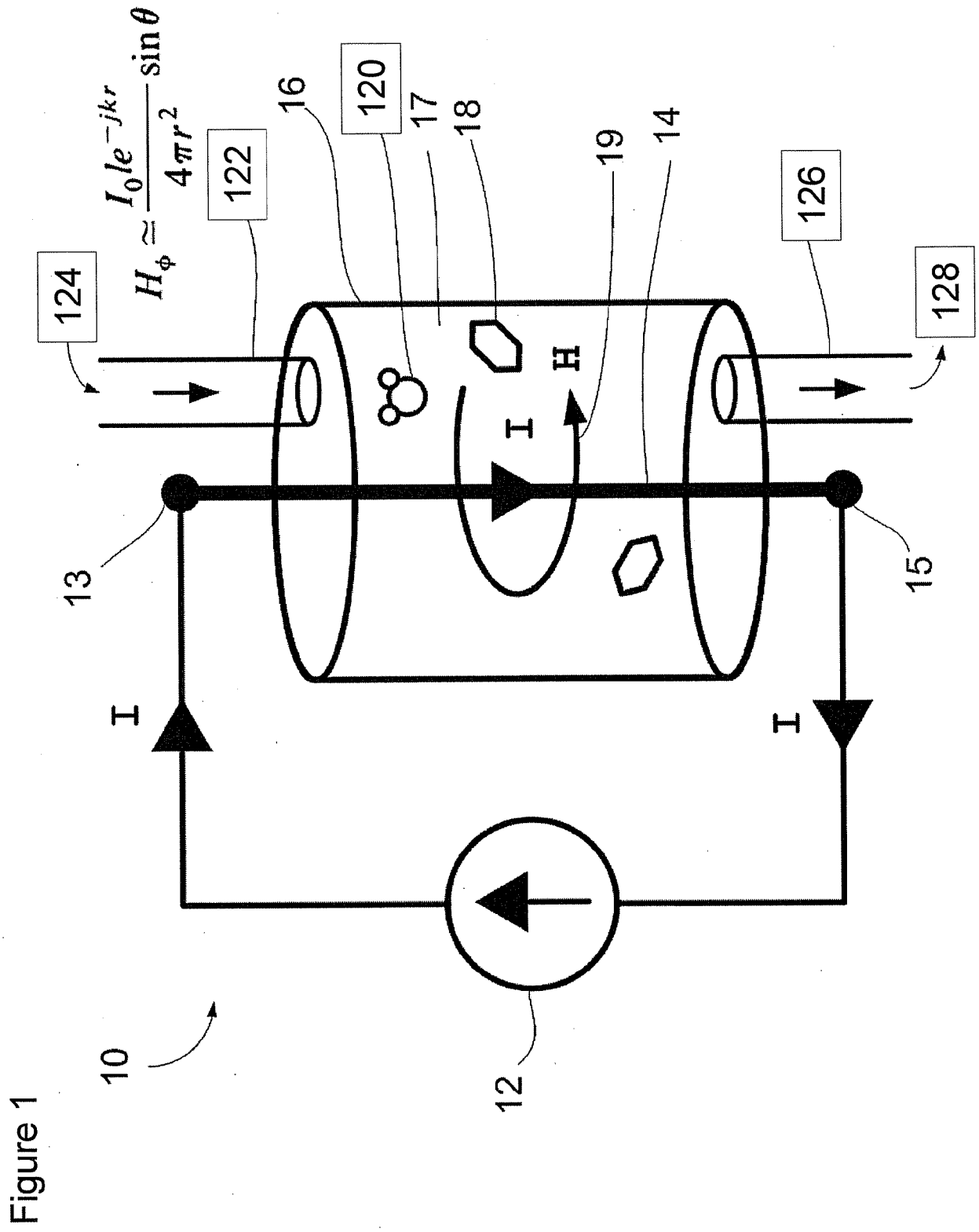
The role of the hydroxyl radical OH $\cdot$ can be important as an initiator molecule. Therefore, exposing hydrocarbon material containing water to radio frequency electric and magnetic fields at frequencies corresponding to the 18 cm transition wavelengths of the hydroxyl radical, for example, at 1612, 1665, 1667 and 1720 MHz can enhance the presence and activity of the hydroxyl radical.

CLAIMS

1. A method for upgrading heavy oil comprising:
placing an applicator into heavy hydrocarbons including aromatic molecules;
5 applying a radio frequency electrical current to the applicator sufficient to
create a magnetic field relative to the applicator to crack at least a portion of the
aromatic molecules into polar molecules; and
processing the polar molecules into fuels.
- 10 2. The method of claim 1 further comprising:
connecting the radio frequency electrical current source to the applicator at a
first connection point and a spaced second connection point, said current source
configured to apply a signal to the applicator sufficient to create a magnetic field and
an electric field around the linear applicator; and
15 positioning a chamber around the applicator between the first connection point
and the second connection point to receive the heavy hydrocarbons.
3. The method of claim 2, wherein the radio frequency electrical current source
comprises:
20 a transmitter configured to transmit radio frequency electrical current;
a transformer having a primary ring and a secondary ring where the transmitter
is electrically connected to the primary ring, the secondary ring is electrically
connected to the applicator at the first and second connection sites, and the primary
ring is configured to adjust relative to the secondary ring to vary the load resistance
25 seen by the transmitter; and
a tuning capacitor electrically connected to the secondary wind-ing to adjust
the transformer resonance to a desired frequency.

4. The method of claim 1, wherein the frequency of the signal applied is between 0.001 MHz and 100 MHz, and at a frequency corresponding to the resonance of the aromatic molecules.
- 5 5. The method of claim 1, wherein the heavy hydrocarbons contain water molecules and further comprising applying the frequency corresponding to the dielectric antiresonance of the water molecules.
6. The method of claim 5, wherein the frequency applied corresponds to the 18
10 cm wavelength of the hydroxyl transition.
7. The method of claim 1, wherein the applicator is a circular applicator.
8. The method of claim 1, further comprising, between the applying and
15 processing steps, separating the hydrocarbons from any water and sand present in the hydrocarbons.
9. The method of claim 1, further comprising, while applying the radio frequency electrical current to the applicator, contacting hydrogen or natural gas with the
20 hydrocarbons to produce synthetic crude oil.
10. The method of claim 1, in which during the applying step the heavy hydrocarbons are located in situ in the ore region of a hydrocarbon formation.

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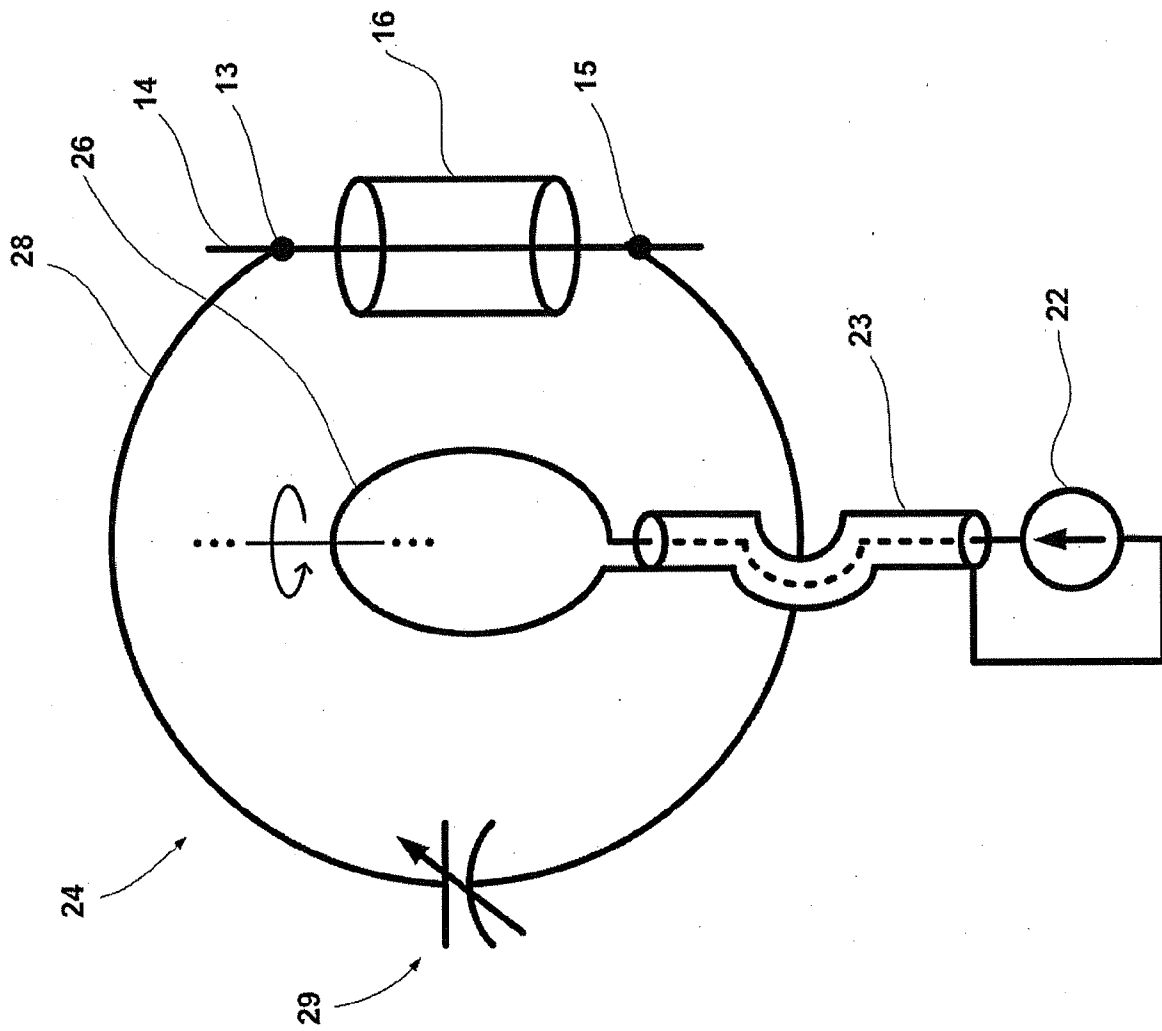
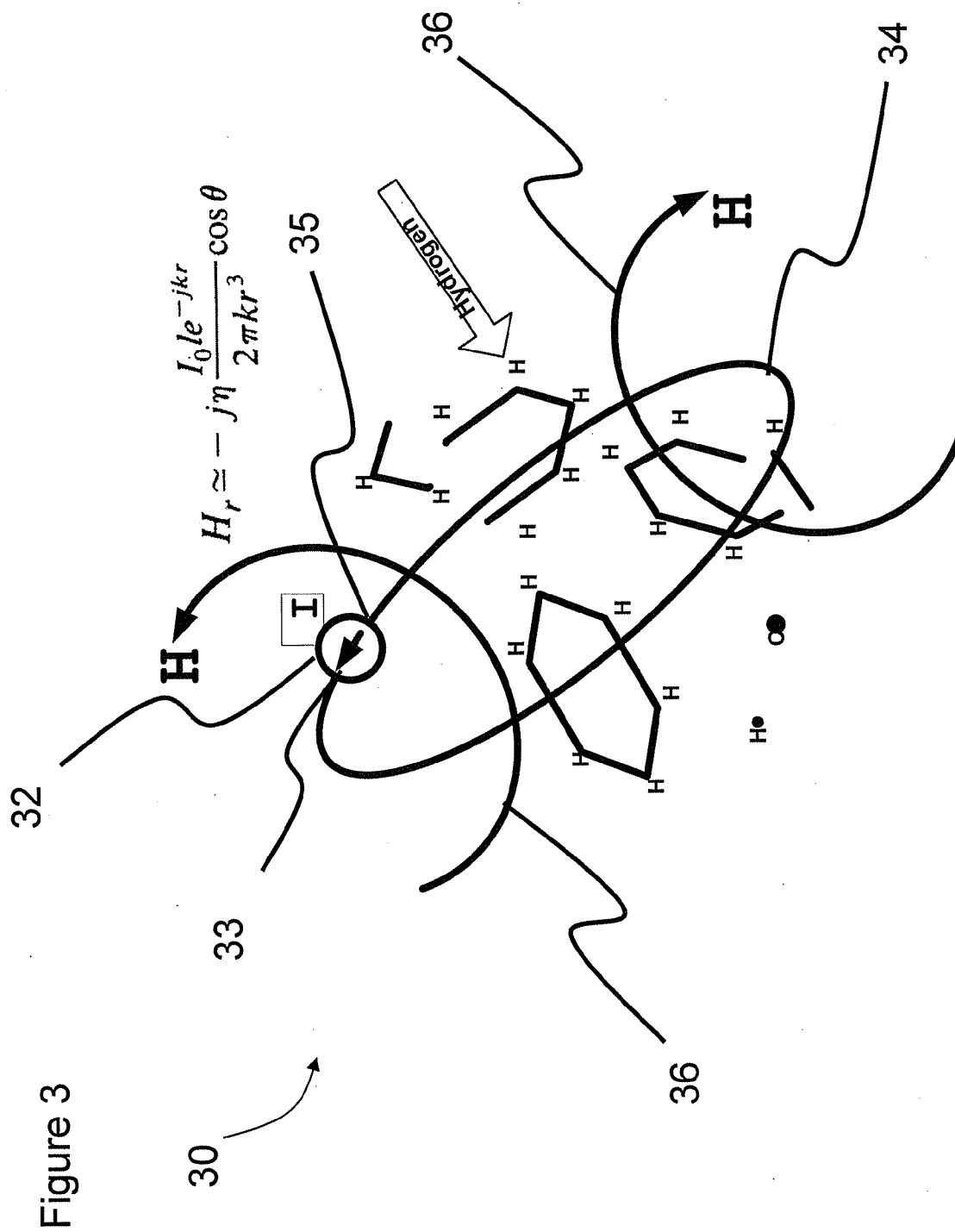


Fig. 2

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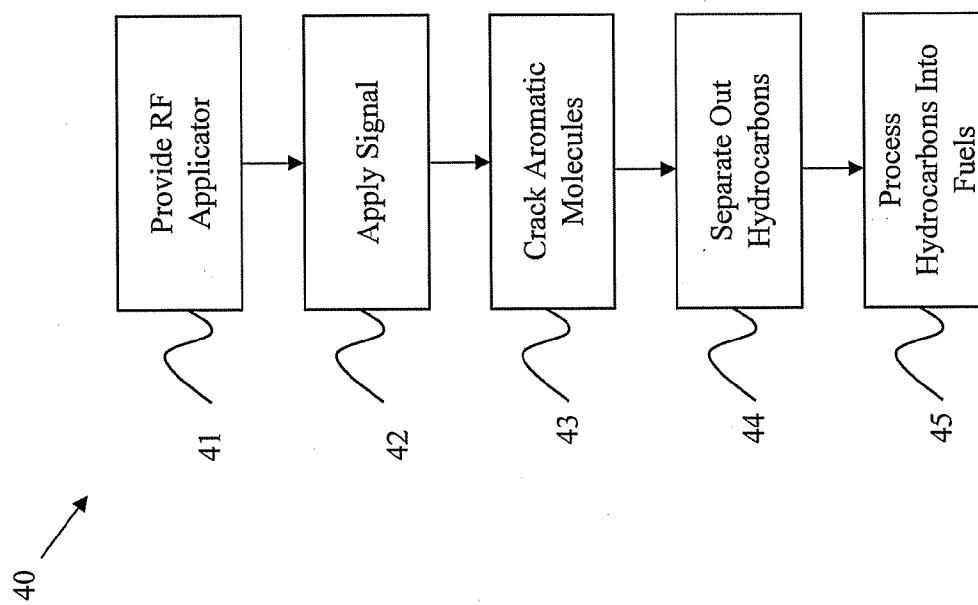
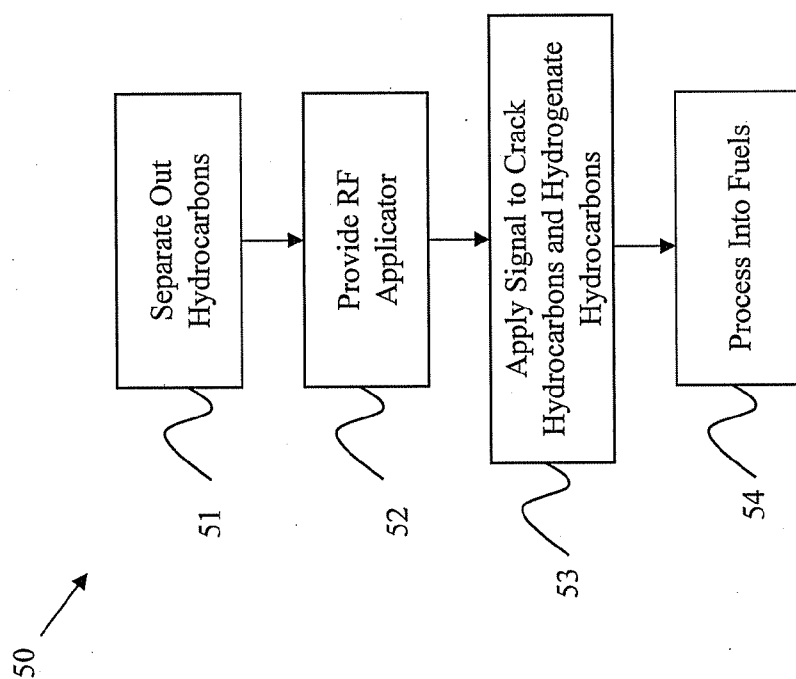


Figure 4

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Figure 5



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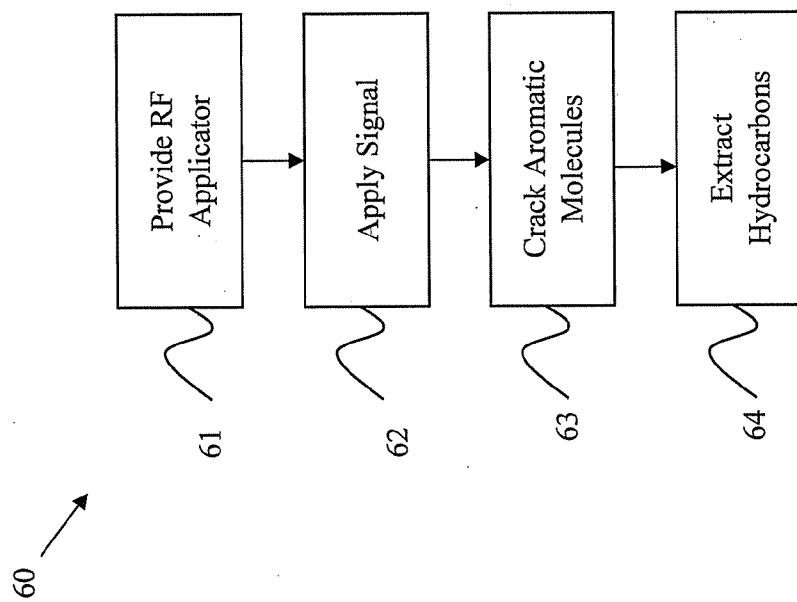


Figure 6

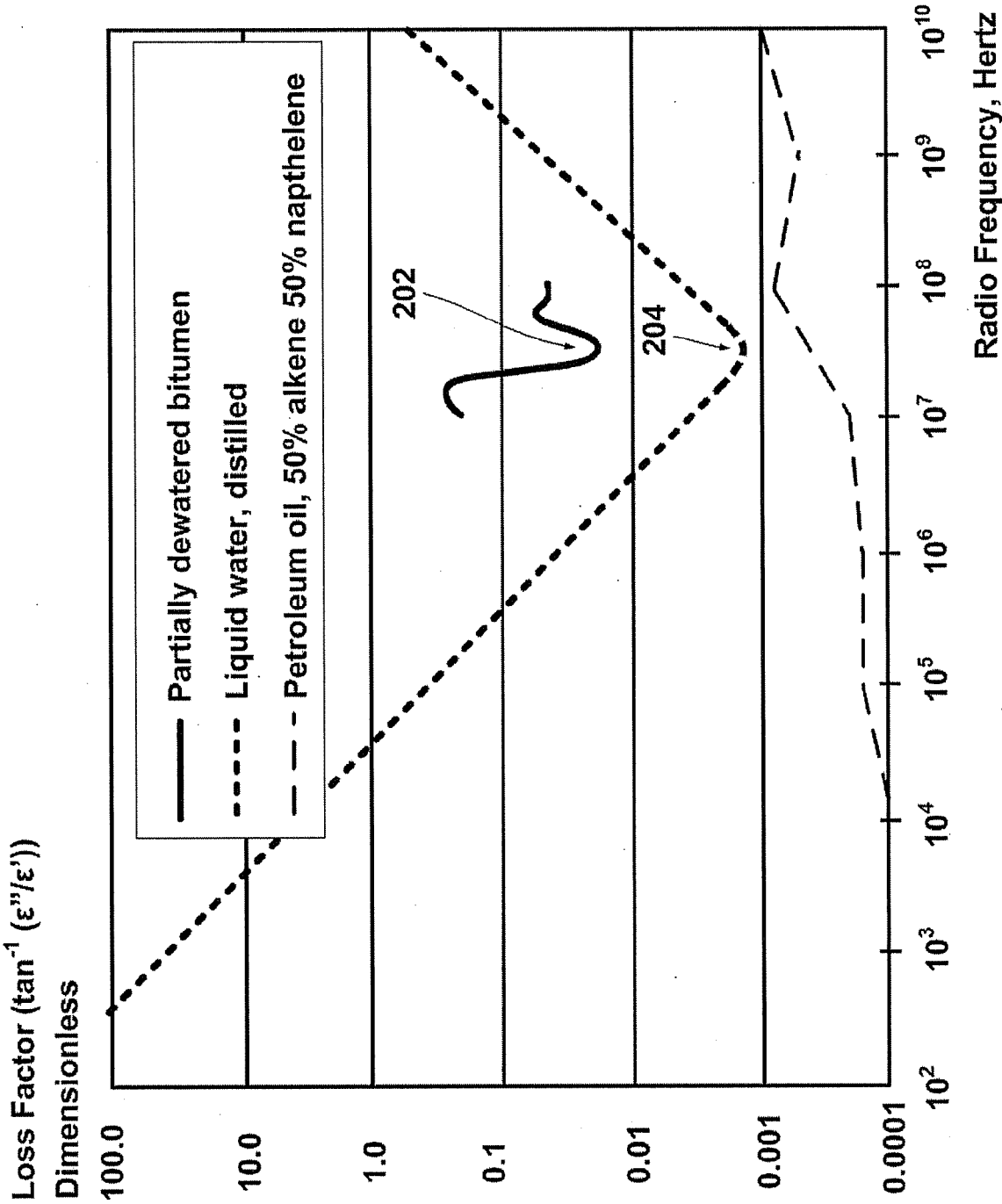


Figure 7

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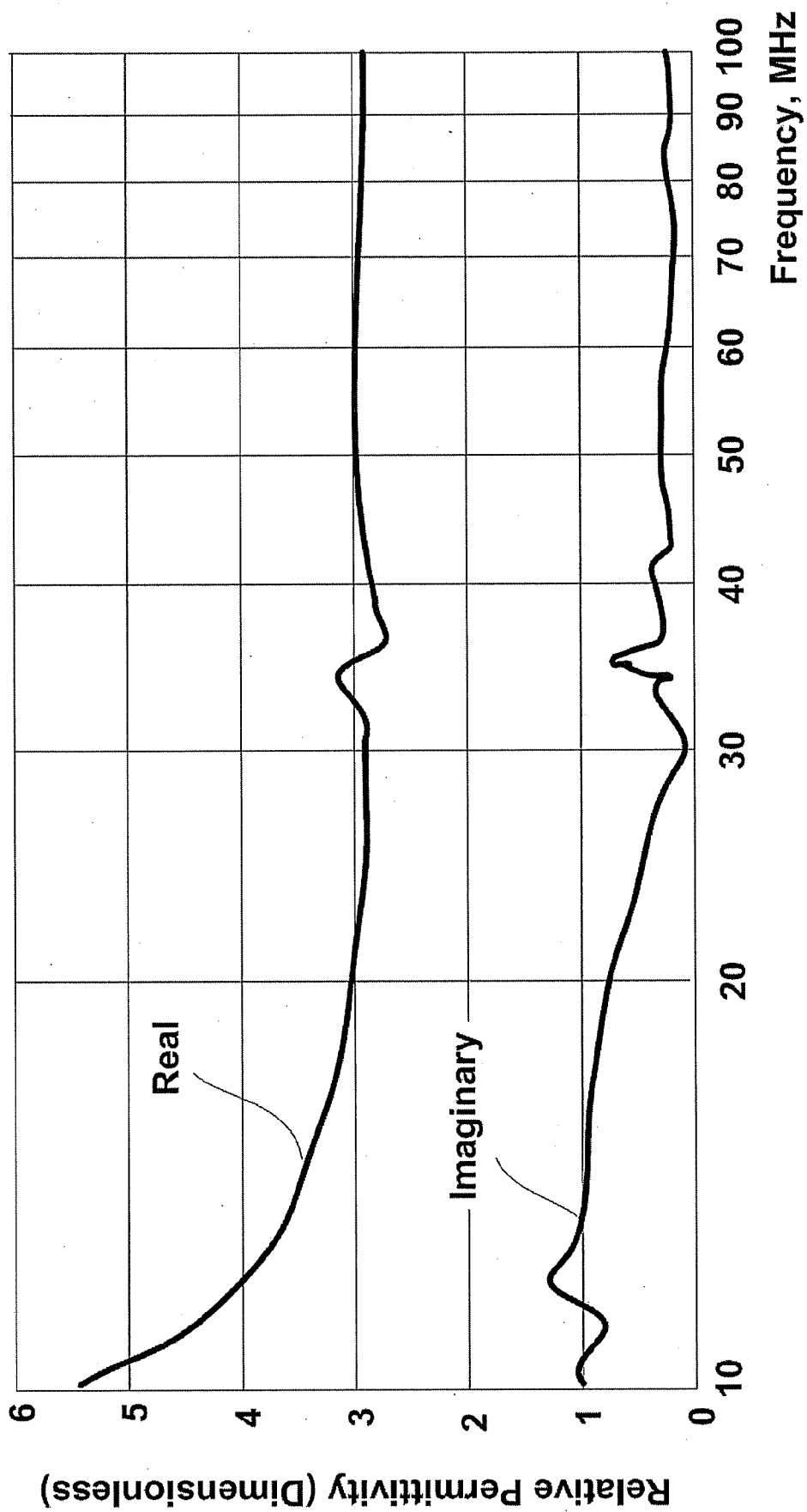


Figure 8

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/031863

A. CLASSIFICATION OF SUBJECT MATTER INV. E21B43/00 C10G1/00 C10G9/00 ADD.		
According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) E21B C10G		
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched		
Electronic data base consulted during the international search (name of data base and, where practicable, search terms used) EPO-Internal		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2005/199386 A1 (KINZER DWIGHT E [US] KINZER DWIGHT ERIC [US]) 15 September 2005 (2005-09-15)	1-10
Y	[0260], [0291]-[0293]; claims 1-25; [0200], [0201], [0202], [0203], [0204]. -----	1-10
X	WO 2008/030337 A2 (KINZER DWIGHT ERIC [US]) 13 March 2008 (2008-03-13)	1-10
Y	fig. 4, 12-16; [0071], [0075], [0076], [0084], [0093], [0101], [0111], [0126]-[0130], [0133], [0153], [0157]. -----	1-10
X	US 4 144 935 A (BRIDGES JACK ET AL) 20 March 1979 (1979-03-20)	1-10
Y	figure 11, col. 14; claims 1-69. ----- -/-	1-10
☒ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
* Special categories of cited documents :		
"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier application or patent but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art "&" document member of the same patent family		
Date of the actual completion of the international search 10 May 2012	Date of mailing of the international search report 24/05/2012	
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Rumbo, Angel	

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/031863

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	L.A. KOVALYOVA ET AL.: "PHYSICAL AND RHEOLOGICAL PROPERTIES OF PETROLEUM FLUIDS UNDER THE RADIO-FREQUENCY ELECTROMAGNETIC FIELD EFFECT AND PERSPECTIVES OF TECHNOLOGICAL SOLUTIONS", APPLIED SURFACE SCIENCE, vol. 238, 17 September 2004 (2004-09-17), pages 475-479, XP002675726,	1-10
Y	point 1.1 Resonant electromagnetic fields interaction with hydrocarbon systems; figures 1,2,5	1-10
X	----- SHUN-I SHIH ET AL.: "DECOMPOSITION OF BENZENE IN THE RF PLASMA ENVIRONMENT. PART I. FORMATION OF GASEOUS PRODUCTS AND CARBON DEPOSITIONS", JOURNAL OF HAZARDOUS MATERIALS, vol. B116, 31 December 2006 (2006-12-31), pages 239-248, XP002675727,	1-4
Y	figure 1; point 3.1-3.3 ; figures 1-8; tables 1, first row	1-10
X	----- SHUN-I SHIH ET AL.: "DECOMPOSITION OF BENZENE IN THE RF PLASMA ENVIRONMENT. PART II. FORMATION OF POLYCYCLIC AROMATIC COMPOUNDS", JOURNAL OF HAZARDOUS MATERIALS, vol. B117, 8 December 2004 (2004-12-08), pages 149-159, XP002675728,	1-4
Y	figure 1; tables 1-4; points 3.1-3.3.	1-10
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Information on patent family members

International application No

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