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Bell et al.

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[54] **ELECTRO-THERMAL PROCESS FOR PRODUCTION OF OFF SHORE OIL THROUGH ON SHORE WALLS**

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[52] **U.S. Cl.** **166/248**, 166/60

[51] **Int. Cl.** **E21b 43/00**

[58] **Field of Search**.............166/248, 272, 60, 65, .6

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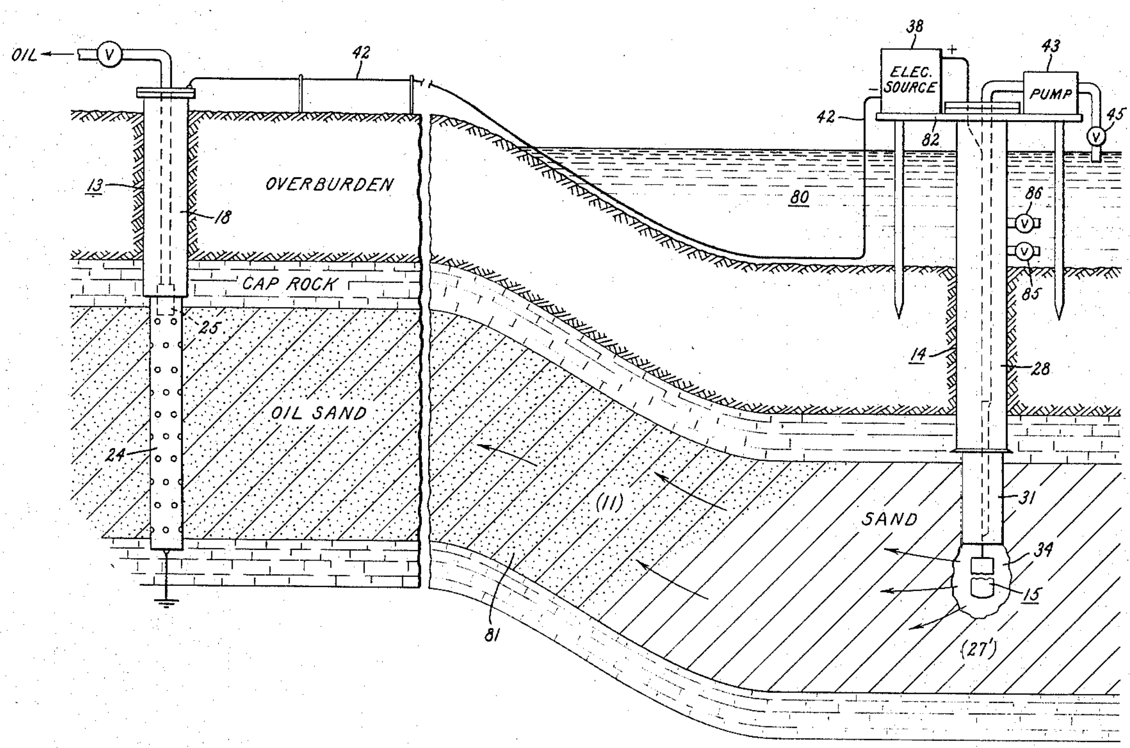
[57] **ABSTRACT**

The flow of oil from an undersea oil-bearing formation to an on-shore well is induced by the steps of locating a relatively small anode in a cavity at an approximately medial elevation of the formation at an off-shore location preferably beyond the reservoir of oil, injecting saline water into that cavity, raising the electric potential of the anode with respect to a cathode in the vicinity of an off-shore well, and withdrawing oil from the well.

10 Claims, 5 Drawing Figures



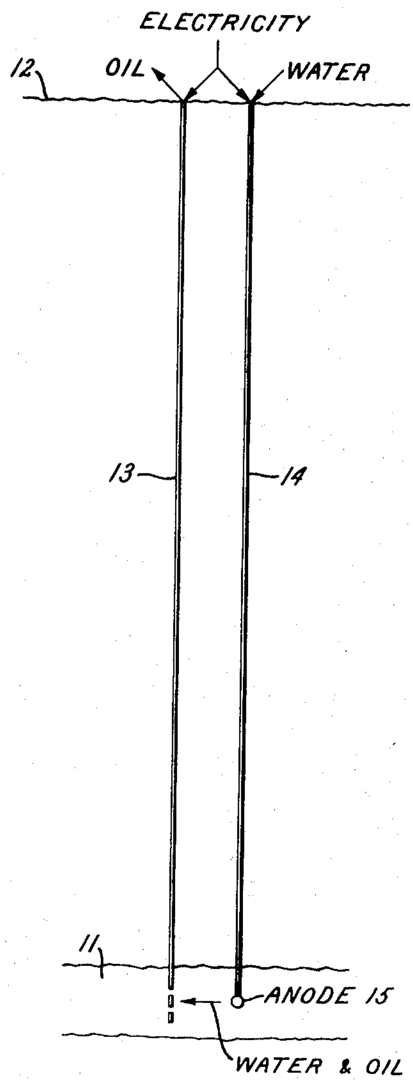
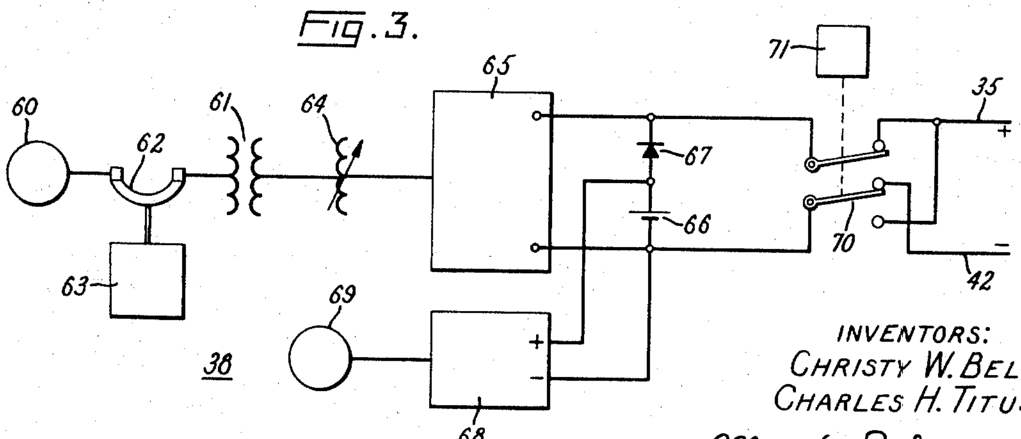


Fig. 1.

Fig. 3.



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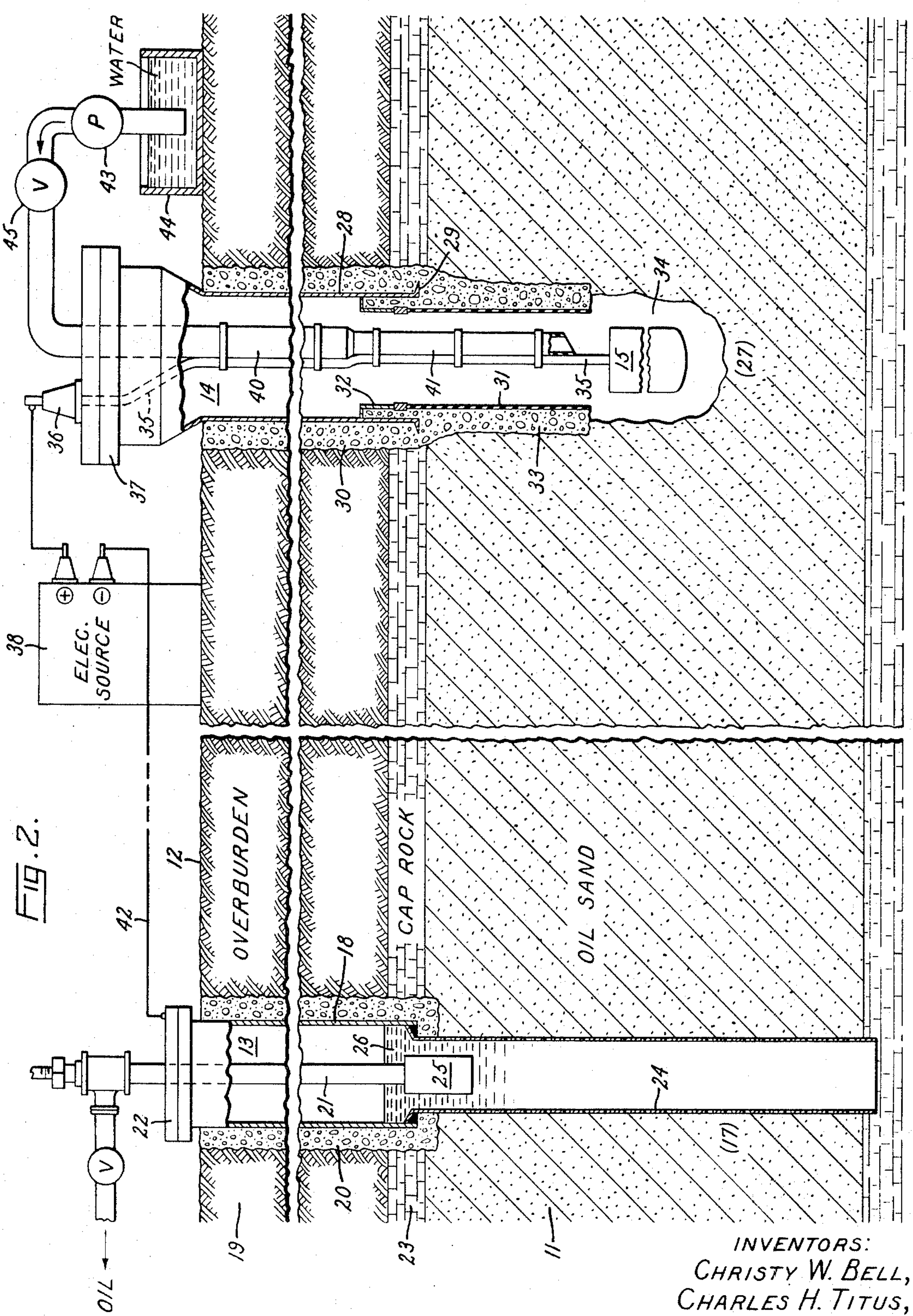

FIG. 2.

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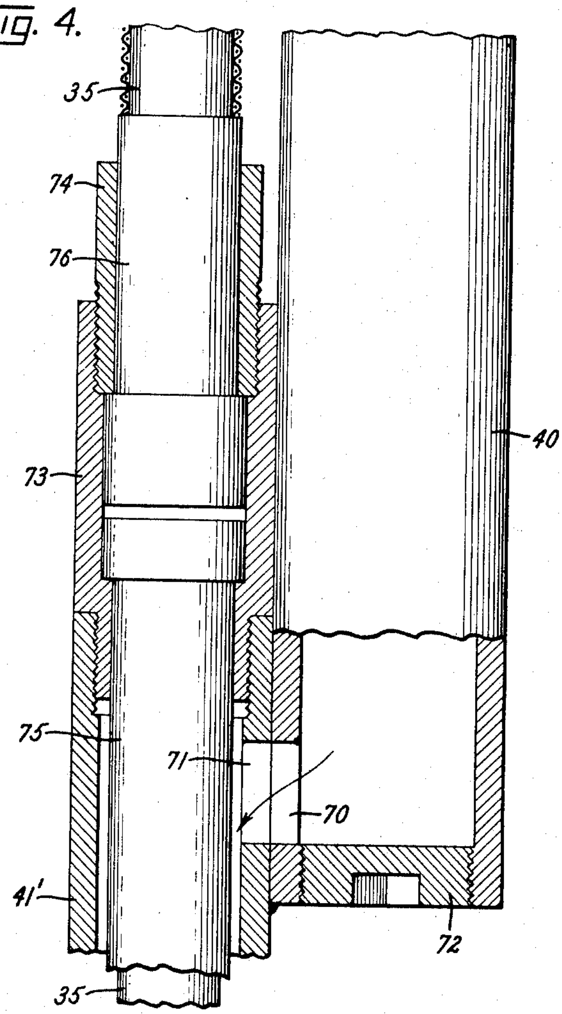
Fig. 4.



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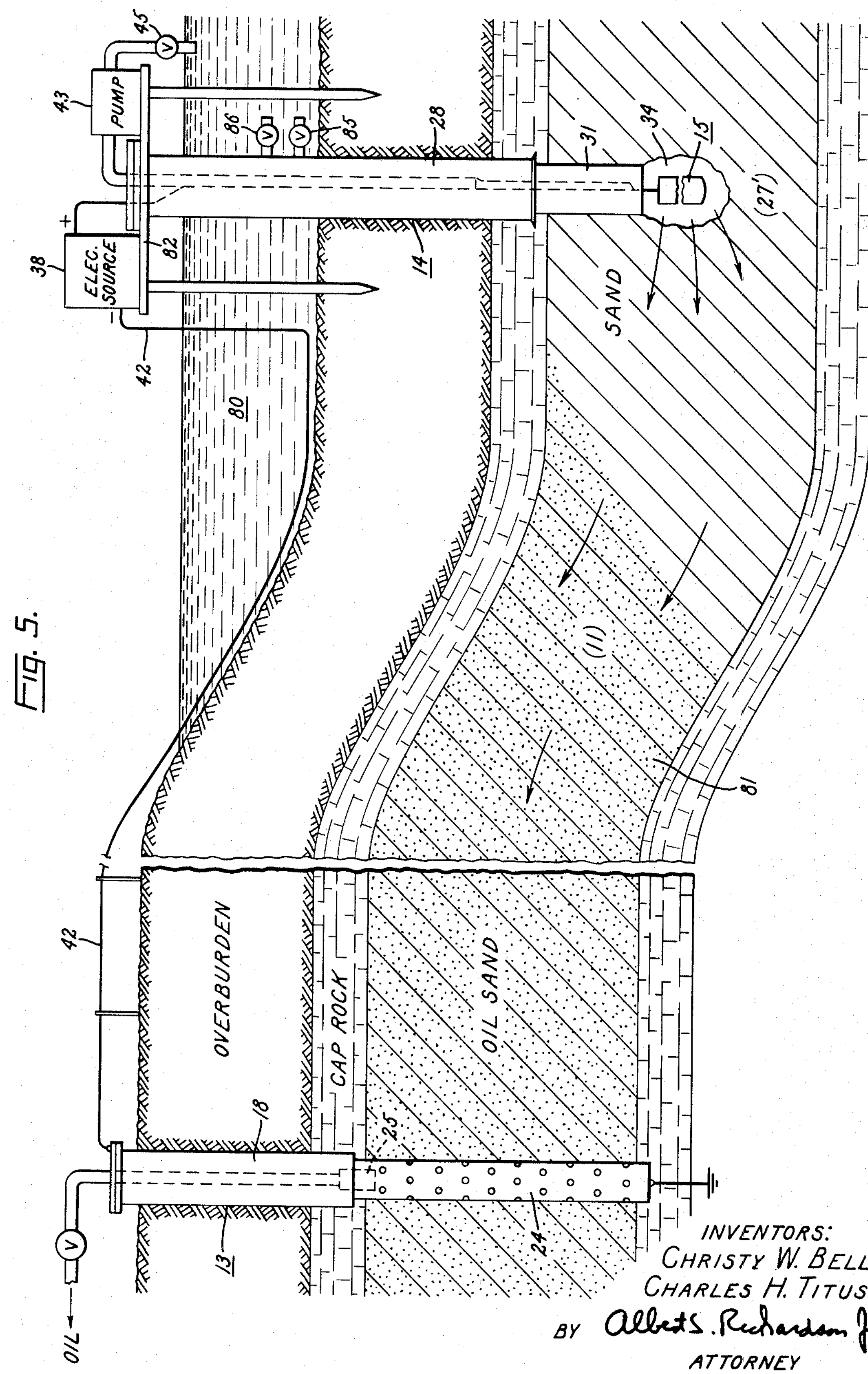

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ELECTRO-THERMAL PROCESS FOR PRODUCTION OF OFF SHORE OIL THROUGH ON SHORE WALLS

Our invention relates to the production of oil from underground oil bearing formations, and particularly to an improved electro-thermal method for producing oil from off-shore regions of a formation through one or more wells in an on-shore region of the formation.

Our earlier application, Ser. No. 855,637, first filed on Sept. 5, 1969, refiled on Nov. 12, 1970 Nov. **9, 1971** and now existing as a continuing application, Ser. No. 196,917 discloses and claims broadly an improved method for utilizing unidirectional electric current to develop electro-kinetic and thermal driving forces in the production of oil. In that application it is pointed out that the method has particular utility in the secondary production of oil from wells in which natural pressure no longer exists and to primary or secondary production where the contained oil is highly viscous. The present invention concerns certain improvements in the foregoing method whereby it is rendered especially applicable to the recovery of oil from undersea or other off-shore oil bearing formations, whether or not the contained oil is under natural pressure or of high viscosity.

Crude oil is generally recovered from an oil bearing formation initially as a result of gas or other formation pressure forcing the oil from the formation into a producing well from whence it is pumped to the surface. Such a well of course must penetrate directly into the body of oil contained in the formation and there is consequent risk that oil under natural pressure will be exhausted without control. To preclude or limit such uncontrolled exhaust it is desirable that oil be moved below ground to a well location remote from the pressurized region or to a well location where surface conditions are such that uncontrolled exhaust may be better controlled at least temporarily. Even where natural pressure does not create the risk of uncontrolled exhaust it may often be desirable to move a body of underground oil, whether fluid or highly viscous, to a well location where production by pumping is less expensive or more convenient than it would be directly over the oil body in its natural location.

The several techniques currently used to induce flow of underground oil are primarily adapted to "secondary" recovery of oil following primary production and may be of limited effectiveness in treating highly viscous oils. A principal such method employs a scavenging fluid such as air, gas, water or steam. In such methods, however, pressure and/or temperature limitations are such that oil flow can be induced only over short distances of the order of several hundred feet and without directional control.

Other prior art techniques for improving oil recovery involve conducting electric current through the oil-bearing strata for the purpose of either raising the temperature of the oil by conduction heating or controlling oil movement by electro-osmosis. The latter is described in U.S. Pat. No. 2,799,641 granted on July 16, 1957 to T.G. Bell whose proposes placing two electrodes in contact with the oil at spaced apart locations in an oil-bearing formation. Bell teaches that electromotive force must be impressed directly on the oil to cause electric current to flow through the oil and postulates that the oil is induced to move by electro-osmosis toward the cathode. Such a method, of course, requires that both the producing well and the anode bore hole penetrate directly into the body of oil contained in the formation, and there is consequent risk that oil under pressures created naturally or otherwise may exhaust through the anode hole.

While much has been published about the phenomenom of electro-osmosis and its more common practical applications to soil drainage and the dehydration of wet ground, we are not presently aware that electro-osmosis has been successfully used commercially to transport underground oil for secondary recovery from an existing well or for recovery at an optional location. There is today an urgent need for improved methods of oil recovery from fields where primary pressure has been exhausted and from tar sands where huge quantities of highly viscous oils exist without natural pressure adequate for recovery. Oil bearing strata located beneath surface areas especially susceptible to pollution or inconveniently located, as beneath a lake, gulf or ocean, present a different problem in urgent need of solution.

Accordingly, it is a general object of our invention to provide an improved electro-thermal method for producing oil from an oil containing earth formation through a well penetrating the formation at a selectable point in or beyond the body of contained oil.

It is a more specific object of our invention to provide an improved electro-kinetic method for producing oil from an underwater oil bearing formation in a way which does not require penetration of the contained oil body at any underwater location.

In carrying out our invention in one form, we suspend an anode in a cavity in an underground formation i.e., earth stratum in at least a portion of which a body of oil is present. This cavity may for example be located at the bottom of a vertical borehole extending from the surface of the earth to a predetermined region of the oil-bearing formation. The anode cavity is disposed at an approximately medial elevation of the proximate region of the formation and may penetrate the contained body of oil or lie laterally beyond it. The relatively positive pole of a source of high-voltage, high-power direct current is connected to the anode (e.g., by means of an insulated cable in the anode hole), and the other pole of the source is connected to a cathode located at or near a well bore which penetrates the formation at a point remote from the anode. The well bore may penetrate the contained oil body or be located beyond it so long as some or all the oil body is located between the well and the anode cavity. The well bore may thus penetrate the formation at a selectable point in or near the body of oil to be recovered.

Preferably the cathode comprises a perforated metal linear in the bottom hole of a producing well. The anode is immersed in a hydrous electrolyte of a composition having the essential characteristics of the connate water present in the oil-bearing formation (hereinafter "formation water") which can be supplied thereto through the anode hole, and its potential is raised to a high level (i.e., 200 volts or more) with respect to the cathode. In this arrangement the anode is in essence a point source of heat, and the water in the cavity will be efficiently heated above ambient to a temperature substantially hotter than 250° F. The hydrostatic pressure exerted by the column of water above the cavity, augmented by externally imposed pressure if desired, subjects the water in the cavity to sufficiently high pressure (e.g., 1,000 p.s.i. and up) so that it remains in a liquid state at its elevated temperature. The hot pressurized water surrounding the anode is saline and thus provides a good electrical conducting medium between the anode and the adjacent oil-bearing formation. Due to hydrodynamic pressure and electroosmotic flow, the hot saline water will move from the cavity in a direction toward the producing well, and the resulting pressure and heat fronts effectively stimulate the flow of oil in the oil-bearing formation. Hydrogen released from the interstitial water by electrolysis at the cathode may be absorbed by the crude oil to beneficially increase its hydrogen content, and oxygen liberated near the anode may unite with the oil in an oxidation process that releases useful heat. The anode is constructed of suitable material to resist adverse electrolytic reaction.

As will be apparent from the foregoing summary, we are using unidirectional electric current and formation water as the prinicpal raw ingredients in a new electrothermal method of stimulating and directing the flow of oil from known reservoirs. These inputs are delivered to the subterranean reservoir where the electric energy is converted to thermal energy (heat), mechanical energy (electroosmotic movement of the formation water), and chemical energy (hydrogeneration and oxidation of the oil) which are effective, in combination, to increase the expulsive forces, decrease the retentive forces acting on the oil in situ and to direct flow of oil to a well in the cathode region. In this manner bulk electric power can be efficiently expended to extract more oil from existing oil fields than is otherwise practical using conventional secondary recovery methods. Furthermore, by using our method the number of wells usually drilled to exploit a given reservoir may be reduced, and flexibility is provided in location of wells relative to the location of an oil deposit. The method is applicable regardless of the character of the oil-bearing formation (e.g., highly viscous tarsands, oil shale deposits, "dead" oil fields or oil under natural pressure whether or not highly viscous). Moreover, our method can be successfully practiced even though initially there is no oil in the particular regions or portions of the formation where the anode hole and well, respectively, are located, so long as a reservoir of oil is present somewhere between anode and cathode.

Our invention will be better understood and its various objects and advantages will be more fully appreciated from the following description taken in conjunction with the accompanying drawings in which:

FIG. 1 is a schematic functional diagram of our improved electro-thermal method of stimulating oil recovery from an underground oil-bearing formation;

FIG. 2 is a diagrammatic view, partly in section, of an oil field showing apparatus by which our method can be practiced in one embodiment thereof;

FIG. 3 is an expanded schematic diagram of the electric power source used in the FIG. 2 apparatus;

FIG. 4 is an enlarged fragmentary view, partially in section, of an alternative embodiment of the tubing string shown in the anode hole of FIG. 2 and

FIG. 5 is a diagrammatic cross-sectional representation of an oil field illustrating the means by which our invention may be utilized to recover oil from an underwater oil bearing formation.

Referring now to FIG. 1, the reference number 11 represents a subterranean formation or earth stratum containing a reservoir or body of crude oil in a porous oil-bearing medium. Typically such oil bearing stratum formations are found beneath the upper strata of earth, referred to generally as overburden, at a depth of the order of 2,000 feet or more below the surface. Communication from the surface 12 to the formation 11 is established through spaced apart boreholes 13 and 14. The hole 13 comprises an oil-producing well, whereas the adjacent hole 14 can be a special hole designed for the transmission of water and electricity to the formation 11.

An anode 15 is lowered through the hole 14 to a medial elevation of the proximate region of stratum formation 11. The chamber or cavity in the oil sand where the anode is suspended is flooded with formation water which preferably is injected through the anode hole under fluid pressure in excess of that existing in the oil reservoir. In accordance with conventional practice, the casing in the hole 14 is sealed in the overburden above the formation 11, and the casing head is capped so that any desired pressure may be developed.

By means of an insulated cable in the anode hole 14, the relatively positive terminal of a high-voltage (at least 200 volts) d-c electric power source is connected to the anode 15. The negative terminal of the same source is connected to a ground electrode in the vicinity of the well 13, as to the metallic tubing in the producing well which thus constitutes a cathode. Between anode and cathode, the electrical resistance of the connate water in the oil sand is sufficiently low so that direct current can flow through this formation from the anode 15 to the lower regions of the producing well 13. The formation is heated conductively by electric current passing through it. It is believed that most of the voltage drop between the terminals of the d-c power source is concentrated near the electrodes. By utilizing an anode 15 of small surface area which extends vertically for only a small portion of the vertical height of the proximate formation 11 and raising the anode potential with respect to the cathode to a suitably high voltage, the temperature of the pressurized water that surrounds it can be raised to at least several hundred degrees Fahrenheit. Thus the water is heated and forced into the adjacent oil-bearing formation under the pressure developed in the anode hole. The water thus absorbed is induced to flow primarily toward the cathode well under the applied pressure and the augmenting directional force of electroosmosis.

In the foregoing manner, heat is efficiently imparted to the oil sand 11. This reduces the resistivity and the viscosity of the oil therein and tends to fluidize the same. The heated oil is entrained by the hot water and is forced under pressure toward the producing well, as is indicated in FIG. 1 by the pointer. As the pressure and heat fronts advance toward the producing well, the temperature is increased in regions of the sand more remote from the anode. Thus the entire reservoir of oil between the anode hole **14** and the producing well **13** is progressively heated, and the oil is forced into the producing well where it is removed by ordinary pumping means. The electrolytic action in the oil-bearing formation may tend to hydrogenate and thereby upgrade the oil that is removed therefrom. The operation of our process continues even after oil migrates away from the vicinity of the anode **15**, and in fact the anode hole **14** can initially be drilled in an oil-dry region of the formation **11** beyond the contained body or reservoir of oil.

Suitable apparatus for practicing our invention is shown in FIG. **2**, and its construction and operation will now be described. As is depicted in this figure, the borehole **13** comprises an oil producing well which penetrates one region **17** of the underground oil sand **11**. The well **13** includes an elongated metallic casing **18** extending from the surface **12** to the cap rock **23** immediately above the region **17**. The casing **18** is sealed in the overburden **19** by concrete **20** as shown, and its lower end is suitably joined to a perforated metallic liner **24** which continues through the bottom hole of the well and down to the underburden. A tubing string **21** is disposed inside the casing **18** where it extends from the casing head **22** to a pump **25** located in the liquid pool **26** that will accumulate inside the liner **24**. Preferably the producing well **13** is drilled and constructed in accordance with common practices in the art, and it operates in the usual manner to withdraw or pump from the bottom hole **26** the mixture of oil and water that flows therein from the adjacent reservoir **11**. Our invention is intended to stimulate the flow of that mixture into the producing well **13**, thereby promoting the recovery of oil from the formation **11**.

In accordance with our invention, another borehole **14** penetrates the oil sand **11** at a region **27** thereof horizontally-spaced from the region **17** with which the producing well **13** communicates. This borehole provides ingress to the region **27** for the anode **15** and for water. While a conventional producing well like the well **13** could be modified for this purpose, we have illustrated in FIG. **2** a borehole **14** comprising a special "anode hole" which will next be described.

The anode hole **14** includes an elongated metallic casing **28** whose lower end is terminated by a shoe **29** disposed at approximately the same elevation as the cap rock **23**, and as usual this casing is sealed in the overburden **19** by concrete **30**. Near the bottom of the hole a tubular liner **31** of insulating material extends from the casing **28** for an appreciable distance into the oil sand **11**. The insulating liner **31** is telescopically joined to the casing **28** by a suitable tubular crossover means or coupler pipe **32**. Preferably the space between the exterior wall of the liner **31** and the surrounding oil sand **11** is packed by high-temperature concrete **33**. Although shown out of scale in FIG. **2** to simplify the drawing, actually, for reasons explained hereinafter, the liner **31** should have a substantial length and a relatively small inside diameter.

Below the liner **31**, a cavity **34** is formed in the oil sand **11**, and in this cavity there is an exposed, cylindrical electroconductive body comprising the anode **15** supported by a cable **35** which is insulated from ground. The anode **15** is relatively short compared to the depth of the proximate region of the oil sand (e.g., substantially less than one-half the depth of region **27**), and it is positioned at an approximately medial elevation in this region. For example, if the region **27** were about 100 feet deep, the center of the anode would be disposed approximately 50 feet below the cap rock **23**. (Obviously the vertical dimensions of the formation **11**, the anode **15**, and liner **31**, and the cavity **34** have been foreshortened in FIG. **2** for the sake of drawing simplicity).

The anode **15** is attached to the lower end of the insulated cable **35** whose other end emerges from a bushing or packing gland **36** in a cap **37** at the top of casing **28** and is connected to the positive pole (+) of an electric power source **38**. Preferably the cable **35** is clamped for support at spaced intervals on a tubing string **40** which is disposed in the casing **28**. The lower section **41** of this tubing string, which section extends axially through the liner **31**, is made of insulating material whereby there is no metal in the zone between the anode **15** and the casing shoe **29** except for the conductor inside the insulated cable **35**.

The negative pole (−) of the electric power source **38** is connected via a cable **42** to an uninsulated conductor or electrode in the producing well **13**. As is shown in FIG. **2**, the perforated liner **24** itself conveniently serves as this electrode (the cathode), and the well casing **18** provides a conductive path between the cathode and the cable **42**. If desired a ground electrode other than the well casing but also in the vicinity of the well **13** may be used as cathode. More details of the electric power source **38** will be explained below in connection with the description of FIG. **3**.

The tubing string **40, 41** in the anode hole **14** conveniently serves as a duct for delivering water from the surface **12** down the hole to the vicinity of the anode **15**. Preferably a pump **43** at the surface is used to drive this water from a suitable reservoir **44** through a control valve **45** and into the upper section **40** of the tubing string. The injected water fills the cavity **34** where it is subjected to a high pressure (e.g., in the order of 1,000 p.s.i. or more) due to the hydrostatic head plus additional pressure externally imposed thereon by the pump **43**, and it therefore can flow from the cavity into the surrounding region **27** of the oil sand **11**. As is the case in known water flooding practice, the apparatus is arranged and operated so as to control the volume flow of water as desired.

The resistivity of the bottom hole water will be relatively low due to its saline content. While salts will probably diffuse therein from the adjacent formation **11**, we presently prefer to inject electroconductive water from the surface. A slightly saline solution having a resistivity of approximately 1,000 ohm-centimeters or less is suitable for this purpose, it being understood that the degree of resistivity is not critical. In addition to being electroconductive, the injected water should have the proper mix of metal salts and other colloidal matter to make it compatible with the native formation **11**. This will minimize or prevent swelling of certain clays which may be in the formation, thereby avoiding any severe reduction in permeability of the formation. In oil fields where natural formation water is readily available, it is preferable that such water be injected into the anode hole **14**, thereby to minimize any disturbance to the chemical balance of the underground formation. Alternatively, surface water could be chemically treated to produce an equivalent hydrous electrolyte, i.e., a fluid of a composition having the essential characteristics (electroconduction and deflocculation properties) of the formation water. In either case, the injection water can also be treated if desired with chemical additives which have other beneficial affects such as enhancing oil production under the influence of the electric fields and current which will be present in the formation **11** between the anode **14** and the cathode **24**.

From the foregoing it will be seen that a supply of formation water (or equivalent) is maintained about and in contact with the anode **14**. Injecting the water from the surface, by a process of regulated flow (see below), ensures that the anode is continuously immersed in a pressurized pool of this fluid. The pool of fluid surrounding the anode constitutes an electroconductive path between this electrode and the adjacent oil sand. If necessary to prevent collapse of the walls of the cavity **34**, the anode can also be surrounded by an inert porous medium such as glass beads or coarse sand having more than approximately 10 percent openings. A desirable alternative is to dispose both the anode **15** and the outlet of the water duct **41** inside a tubular container or basket having sidewalls of porous, insulating material, whereby a backflow of oil and sand is effectively prevented and the stream of injected water is directed over a substantial portion of the surface of the anode body before dispersing to the adjacent region **27** of the formation **11**.

In practicing our improved method of stimulating oil recovery, an electric potential is applied to the anode **15** so as to raise its voltage, with respect to the remote region **17** of the formation **11** where the producing well **13** is located, to a relatively high level (i.e., of the order of several hundred to several thousand volts). Consequently current will flow through the formation **11** between the anode **15** and the producing well **13**. The connate water in the intersticies of the oil sand initially provides a path for this current, and its temperature is raised thereby. Interstitial water typically constitutes only on the order of 15 percent of the formation **11** by volume, and the resistance of the conducting path through this formation will be much higher than that of the mass of saline water which immediately surrounds the anode **15** in the cavity **34**. Nevertheless, because the current density in these conducting media is highest next to the relatively small surface area of the anode and decreases as an exponential function of the distance (radius) therefrom, a high percentage of the voltage drop between the anode and the ground is expected to be concentrated near the interface of the water mass and the adjoining oil-saturated region of the formation **11**. As a result, a great deal of electric power dissipates in the vicinity of this interface, and the temperature of the pressurized water around the anode **15** will be raised appreciably. We contemplate a power input of the order of 25 to 1,000 kilowatts or more, which may heat the water in the cavity **34** to a temperature substantially in excess of 250° Fahrenheit. This hot water is maintained in a liquid state by appropriately regulating both its temperature and its pressure. For example, the hydrostatic pressure of a 2,000 foot column of water exceeds 900 p.s.i., and at this pressure water remains liquid to approximately 530° F.

It should be noted at this point that the vertical column of saline water above the cavity **34** will not form a short circuit between the anode **15** and the metallic casing **28** of the anode hole **14**. This is because the water column is confined in a long, narrow space having a relatively small cross-sectional area. The dimensions of the insulating liner **31** through which the water is injected are selected so that the resistance of the confined water, if measured between the top of the anode **15** and the lower end of the casing **28**, will be appreciably higher than the resistance of the conducting path through the oil sand between anode and cathode. Due to its close proximity to the source of heat, the bottom part of the insulating liner **31** is adventageously made of high-temperature material.

Within the underground formation **11**, the temperature of the oil region adjoining the pressurized hot water in the cavity **34** is elevated by this source of heat, whereby both the viscosity of the oil and the resistivity of the oil bearing sand are reduced. As hot oil recedes from the anode **15**, more conductive saline water fills the vacated space in the porous media. The heat dissipated per unit volume of saline water will decrease near the anode where the resistivity of the water has decreased due to the temperature increase. Thus a heat front advances toward the cathode and behind it displaced oil is replaced by hot injected water. Because a substantial portion of the impressed unidirectional voltage appears at this advancing interface heat is continuously generated electrically in the immediate vicinity of the front to maintain the action.

In operation, our invention causes a stream of hot water and oil to flow in the formation **11** toward the producing well **13**. This stream is driven by water injected into the anode hole **14**, and it is guided toward the cathode by electro-osmosis. The latter effect can be attributed to a net movement of ions in the interstitial water under the influence of a unipolarity field. This electro-osmotic motive force supplements applied water pressure in the region between electrodes and promotes a migration of heating water from the cavity **34** through the porous oil sand to the producing well **13**. In a given medium the volume flow of water due to electro-osmosis depends on the magnitude of current being conducted. Because the sand particles in the native formation **11** are predominantly water wet and because the residual oil tends to adhere, by interfacial tension, to the contiguous water film on these particles, this electro-osmotic mode of transporting water through the capillaries and crevices of the oil sand is particularly effective in achieving the desired result of transferring heat and motion to the residual oil.

Some of the electric energy supplied to the electrodes in our invention will be utilized to liberate hydrogen from the water in the pool **26** at the bottom of the producing well **13**. This electro-chemical action is well known as electrolysis. Because the formation **11** is not homogeneous, there are anomalies in its conductivity that form a series of local anodes and cathodes between the main electrodes **15** and **24**. Consequently, hydrogen and other gases will be electrolytically released throughout the formation. Some of the gasses, such as chlorine, will chemically react to form certain beneficial acids which promote formation of appropriate porosity and fluid flow in the oil sand. The union of hydrogen and warm oil may partially hydrogenate the oil that is extracted from the formation 11 thereby improving the grade and the value of the recovered oil. Furthermore, the unipolarity electric field between the main electrodes may raise the peak kinetic energy of mobile charged particles in some areas of the underground formation to a sufficiently high level to produce fractional distillation and further upgrading of the oil in situ. Gasses thus liberated and not absorbed or reacted may accumulate in higher strata and develop pressure which supplements other forces driving oil toward the well 13.

In the cavity 34 electrolytic action contributes to a hostile environment for the anode 15 and associated parts of the apparatus disposed at the bottom of the anode hole. In operation oxygen and other corrosive gases and chemicals are liberated at the anode. Electrolytic action will tend to deplate or consume certain positively energized metals. Therefore care should be exercised in designing the anode 15 so that its surface, which is the only exposed conductor in the bottom of the anode hole 14, will resist both chemical and galvanic corrosion.

To ensure a sound mechanical and electrical connection between the cable 35 and the anode 15 under the foregoing difficult conditions and in the high-pressure ambient at the contemplated depth of the anode hole, it is believed desirable that the cable be inserted, as by a threaded conducting plug connection, into a recess in the anode. The lower section of the cable and the juncture of the plug and the anode should then be covered with insulation which has adequate dielectric strength and is impervious to oxygen and other deleterious chemicals. There is a possibility that a high pressure differential between the exterior surface and the interior recess of the anode may damage the anode. To protect the interior surface of the anode it is desirable to fill any voids in the anode recess with suitable high gravity electroconductive liquid and to close the recess with a pressure-equalizing seal. The exterior surface of the anode body should be the only part of the apparatus from which current enters the surrounding saline water, and it is resistant to chemical attack and deplating.

An electric power supply suitable for energizing the anode 15 has been shown in FIG. 3. The availability of three-phase a-c high-voltage service is assumed, and in FIG. 3 this service is illustrated symbolically at 60. The high voltage is fed to the primary windings of a power transformer 61 through a conventional circuit breaker 62 which is equipped with an operating mechanism 63 for opening and closing the primary circuit on command. The secondary circuit of the power transformer 61 is connected to a controlled converter which is constructed and arranged to apply across the conductors 35 and 42 a unipolarity output voltage of controllable magnitude. The illustrated converter comprises an adjustable autotransformer 64 in series with a high-power rectifier 65. The average magnitude of its output voltage can be varied from a few hundred volts to thousands of volts. This can be done manually or, if desired, automatically by suitable means well known in the pertinent electrical art.

In operation, the load on the power supply 38 is expected to vary after the anode 15 is first energized. The resistivity of the saline water tends to decrease with increasing temperature in the formation 11. The presently preferred mode of controlling the electric power and water inputs of our process will now be explained. The magnitude of current in the cable 35 is regulated by suitably adjusting or programming the applied voltage. In this way the electric current between anode and cathode can be held at a desirable preset level. To prevent excessive heating of the anode itself, the electroconductive fluid supplied through the anode hole 14 is suitably controlled so as to vary the value of its volume rate of flow as a function of the electric energy dissipated underground. This can be accomplished, for example, by employing appropriate means for controlling the rate of flow of the injected fluid in accordance with the product of the magnitude of applied voltage and the magnitude of anode-to-cathode current, whereby the desired rate of fluid flow is determined by the amount of input power. As the input power increases, so does the quantity of injected fluid thereby beneficially increasing the cooling effect on the anode 15. A maximum pressure override should also be provided to prevent excessive underground pressure which might fracture the formation 11.

For optimum utilization of the input power without excessive heating, it may be desirable to open the circuit breaker 62 for a certain interval or intervals of time during which oil can continue flowing in the oil-bearing formation due to the energy retained therein. If and when the primary circuit is deenergized, a low-voltage (e.g., 12 volts) positive bias is preferably maintained on the anode 15 to minimize adverse galvanic action in the anode hole, and toward this end a battery 66 is connected in series with an isolating diode 67 across the output terminals of the rectifier 65. To recharge the battery 67, it is connected to a conventional battery charger 68 which is coupled to a suitable source 69. This positive bias means, which is not our joint invention, is more fully described and is claimed by C.H. Titus and H.N. Schneider in a copending patent application Ser. No. 117,488 filed on Feb. 22, 1971 assigned to the assignee of the present invention.

It may be advantageous to reverse from time to time the unipolarity voltage applied between the cables 35 and 42. Toward this end, suitable reversing means is optionally provided. By way of example, FIG. 3 shows a polarity reversing switch 70 between the rectifier 65 and the cables, with the position of this switch being controlled as desired by an associated mechanism 71. Ordinarily the reversing cycle would be asymmetrical so that there is a net electroosmotic movement of water through the oil sand in the direction of the producing well 13. The reactance of the cable 35 in the anode hole 14 will not seriously impede the flow of current through this path so long as either direct current or low-frequency reversible current is being supplied. In view of these alternative modes of practicing our invention, the terms "d-c" and "unipolarity" are meant herein to apply to quantities whose direction of influence can be reversed during or after a cycle of operation of our process without reducing to zero the average influence of the quantity in that direction during that cycle.

When our process is operated in either the discontinuous power mode or the reverse polarity mode described in the preceding two paragraphs, respectively, it is possible to use the anode hole as a producing well for extracting oil from the proximate region **27** of the formation **11**. Furthermore, it is possible to use our invention to recover oil from a subterranean formation in a push-pull fashion where there is only a single borehole communicating with the surface of the ground.

FIG. **4** shows an alternative arrangement for joining the two sections **40** and **41** of the tubing string in the anode hole **14**. In FIG. **4** the lowest part of the upper section **40'** of the tubing string is secured in side-by-side relation to the top part **41'** of the lower section, and these parts are respectively provided with registering slots **70** and **71** which permit the injected water to flow from the section **40'** into part **41'**. The bottom of section **40'** is closed by a suitable plug **72** as shown. The top of part **41'** is provided with a packing gland for admitting the cable **35**. As is shown in FIG. **4**, this gland includes cooperating threaded sleeves **73** and **74** between which the shoulders of a pair of tubular metal clamps **75** and **76** are captured. The insulated cable **35** passes vertically through this assembly, and its lower portion is therefore disposed inside the lower section of the tubing string. At an elevation below what is shown in the fragmentary view of FIG. **4**, the metal part **41'** is connected to an insulating tube, and the metal clamp **75** is terminated. There are two principal advantages of this "Zee" assembly. It protects the cable **35** from damage during installation of the anode **15**, and it directs the injected water around the lower portion of the cable **35** and directly over the top of the anode **15** for improved cooling of the surfaces of these conductors. The Zee assembly is more fully described and is claimed by C.H. Titus and H. N. Schneider in U.S. Pat. No. 3,674,912 filed Feb. 22, 1971 and assigned to the same assignee as is the present application.

At FIG. **5** we have illustrated schematically a modified form of apparatus whereby our invention may be practiced in a particular embodiment made available when all or a portion of the reservoir of oil in an oil bearing formation lies under a body of water, and in particular under saline water, as offshore under the sea. In the embodiment there illustrated the earth structure including an oil bearing formation **11** is shown in substantially the same manner as at FIG. **2** except that part of stratum formation **11** lies under a body of seawater **80**. At FIG. **5** the anode hole **14** is located in a region **27'** of the stratum formation **11** which is laterally contiguous to but beyond the body or reservoir of oil **81** contained in the formation and below an off-shore area of the earth's surface. The electric power source **38** and pump **43** associated with the anode hole are mounted on a sea platform **82** and the anode hole casing **28** extends to the platform.

The water inlet to the pump **43** is shown connected to the seawater **80** as a supply reservoir, but it will be understood that other appropriate sources of water for injection may be used, as described heretofore. If seawater is used it may require certain chemical additives of the type previously mentioned, but due to its accessibility to an offshore anode hole it is to be preferred. Use of seawater in an offshore anode region offers the further advantage that hydrostatic pressure of the sea itself may be used in place of the pump **43** to supply the added pressure required to inject water at the anode cavity. To illustrate such a water supply source we have shown two water inlet valves **85** and **86** located on the anode casing **14** at different depths beneath the surface of the sea **80**. A selected one of these valves may be opened (with the pump shut down) to admit sea water at a desired pressure to the anode cavity. Any desired number of such inlet valves may be provided at different pressure levels.

The producing well **13** at FIG. **5** is shown in an onshore location with metal liner **24** electrically connected to ground and through a cable **42** to the negative terminal of the d-c supply source **38**, as at FIG. **2**. While this well is shown as penetrating the oil body **81**, it will now be understood that if desired it may be located initially beyond the body of oil **81** between the electrodes.

In summary it will be seen that we have marshalled a number of different forces toward the desired end of efficiently utilizing bulk electric power to increase the amount and the value of oil extracted from underground reservoirs. While most useful in combination, all of these forces do not necessarily have to be employed in concert to obtain satisfactory results.

In spite of the high potential contemplated at the anode **15**, the voltage gradient near the surface **12** of the ground will be small or negligible. Therefore our invention can be practiced safely. Where necessary, conventional cathodic protection can be used to retard corrosion of underground pipe lines, if any, in the vicinity of the surface.

While we have shown and described one form of our invention by way of illustration, many modifications will occur to those skilled in the art. For example, a single anode hole can be used in combination with a plurality of spaced producing wells **13** which are connected, either concurrently or in sequence, to the negative pole of the electric power source **38**, or a plurality of anode holes could ring a common producing well. The insulating liner **31** could be extended; e.g., the lower end of the liner could define the cavity **34** and circumvent the anode **15**, with its sidewall being perforated to permit egress of the heated water. We therefore desire herein to cover all such modifications as fall within the true spirit and scope of our invention.

In this application we have disclosed exemplary apparatus that now appears useful in conjunction with the practical implementation of the oil-recovery process we invented. To the extent this ancillary apparatus includes novel and nonobvious features such features are not themselves part of our present joint invention, and patent applications thereon may be filed in the name or names of those persons who were the original and first inventors thereof.

What we claim as new and desire to secure by Letters Patent of the United States is:

1. An electro-thermal method for stimulating flow of oil from a porous and substantially homogeneous underground oil bearing stratum formation having a first region including a body of oil penetrated by a well bore and a second region laterally contiguous to said oil body which comprises,

a. locating an electrode in a cavity in said second region and outside said oil body, said electrode being sufficiently small to constitute effectively a point source of resistance heating and said cavity being positioned at an approximately medial stratum elevation in the proximate portion of said second region,

b. immersing said electrode in a pressurized conductive fluid constituting an electro-conductive path between the electrode and said formation, said fluid forming an expanding body of liquid surrounding said electrode,

c. locating an exposed conductor in current conductive relation with said formation in the vicinity of said well bore,

d. applying a unipolarity voltage between said electrode and said conductor, said electrode being positive relative to said conductor, the resulting unidirectional current through said porous formation having sufficiently high density at the surface of said electrode to heat said liquid body appreciably above the surrounding ambient temperature of said formation as said liquid body expands, and

e. extracting oil from said body of oil through said well bore.

2. The method of claim 1 wherein said pressurized fluid substantially continuously injected under pressure sufficient to ensure flow thereof into said formation from said cavity.

3. An electro thermal method for directing flow of oil from an off-shore underground oil bearing stratum formation to an on-shore well bore penetrating the formation which comprises,

a. locating an electrode in a cavity in an offshore region of a porous and substantially homogeneous oil bearing formation and at an approximately medial elevation in the proximate portion of said off-shore region, said off-shore region being selected to include between said wellbore and said cavity at least a portion of a body of oil in said formation and said electrode being sufficiently small to constitute effectively a point source of resistance heating,

b. immersing said electrode in a pressurized conductive fluid constituting an electro-conductive path between the electrode and said formation, said fluid forming an expanding body of liquid surrounding said electrode,

c. locating an exposed conductor in said formation in the vicinity of said well bore and in current conductive relation with said formation,

d. applying a unilateral voltage between said electrode and said conductor with said electrode being positive relative to said conductor, the resulting unidirectional current through said porous formation having sufficiently high density at the surface of said electrode to heat said liquid body appreciably above the surrounding ambient temperature of said formation as said liquid body expands, and

e. extracting oil from said body through said well bore.

4. The method of claim 3 wherein said cavity is located in a region of said formation contiguous to but beyond said body of oil.

5. A method according to claim 3 wherein said body of oil lies only partially off shore and is penetrated by said well bore.

6. The method of claim 3 wherein said oil body surrounds said cavity.

7. The method of claim 3 wherein said off-shore region is under a body of saline water and said saline water is introduced into said cavity to immerse said electrode.

8. The method of claim 7 wherein said cavity is exposed to said body of saline water at a predetermined depth below the surface thereof.

9. The method of claim 7 which includes also opening said bore hole to admit saline water from said body of water at one of a plurality of selectable depths below the surface of said water.

10. The method of claim 3 which includes also maintaining said fluid substantially continuously under pressure sufficient to ensure flow of fluid into said formation from said cavity, whereby current between said electrode and conductor heats said fluid and directs its flow toward said well bore.

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