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Bell et al.

[11] **3,782,465**

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[54] **ELECTRO-THERMAL PROCESS FOR PROMOTING OIL RECOVERY**

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[21] Appl. No.: **196,917**

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 88,854, Nov. 12, 1970, abandoned, and a continuation-in-part of Ser. No. 855,637, Sept. 5, 1969, abandoned.

[52] **U.S. Cl.** **166/248,** 166/272

[51] **Int. Cl.** **E21b 43/24**

[58] **Field of Search** 166/248, 302, 272

[56] **References Cited**

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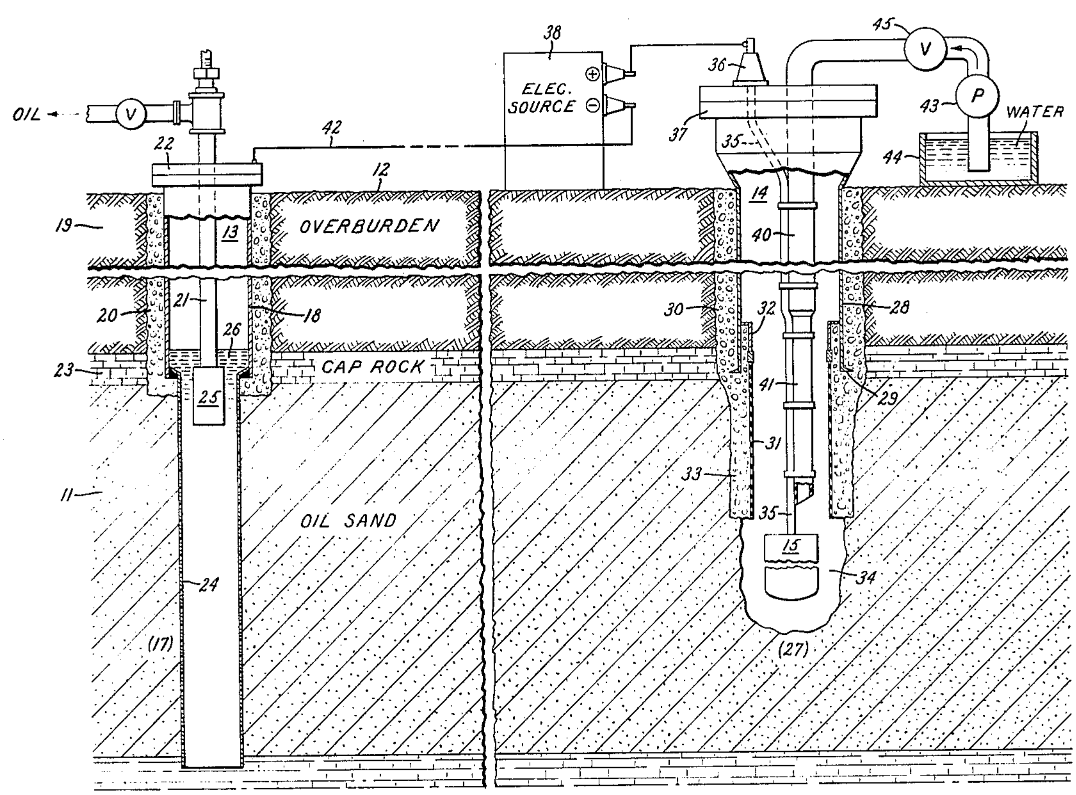
[57] **ABSTRACT**

The flow of oil from underground oil-bearing formations is stimulated and directed by the steps of locating a relatively small anode in a cavity at an approximately medial elevation of one region of the formation, injecting saline water into that cavity, raising the electric potential of the anode with respect to a laterally adjacent region of the formation, and withdrawing oil from a producing well penetrating said adjacent region.

19 Claims, 6 Drawing Figures



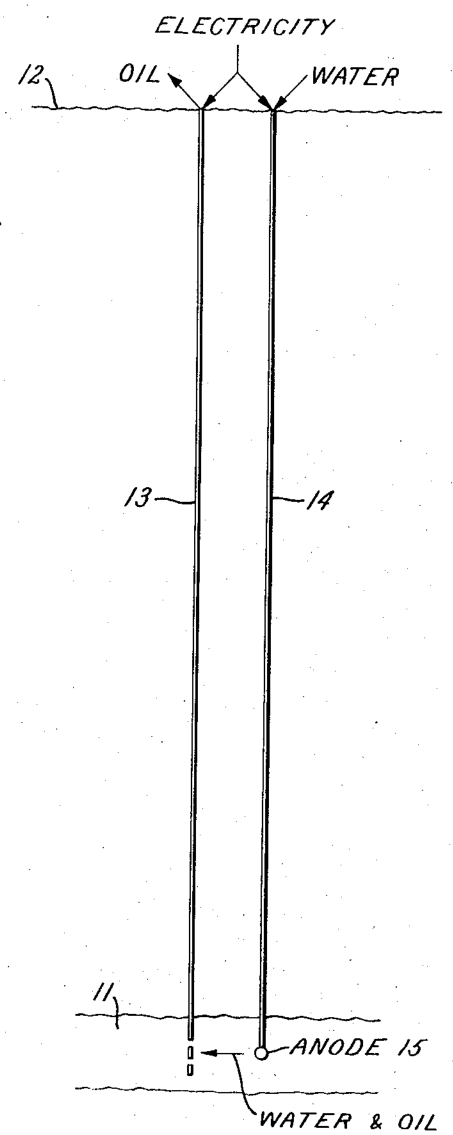


Fig. 1.

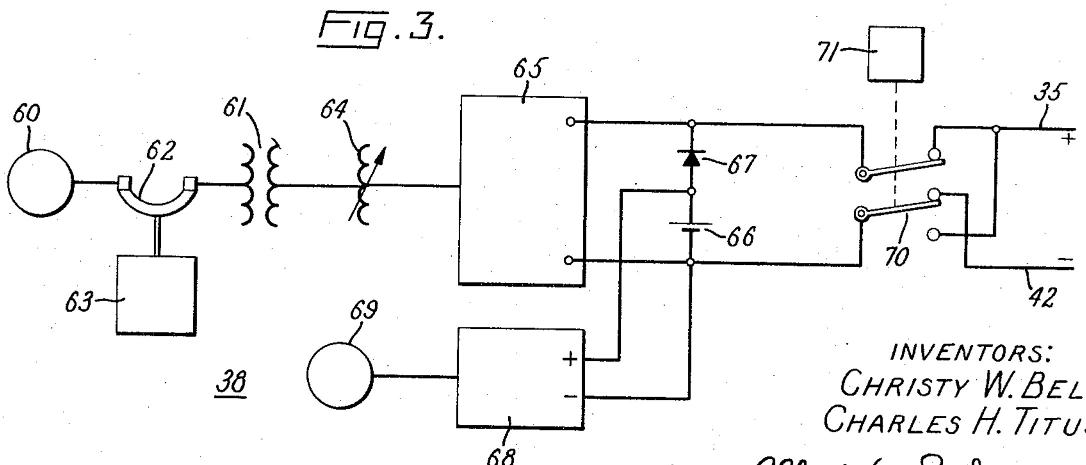


Fig. 3.

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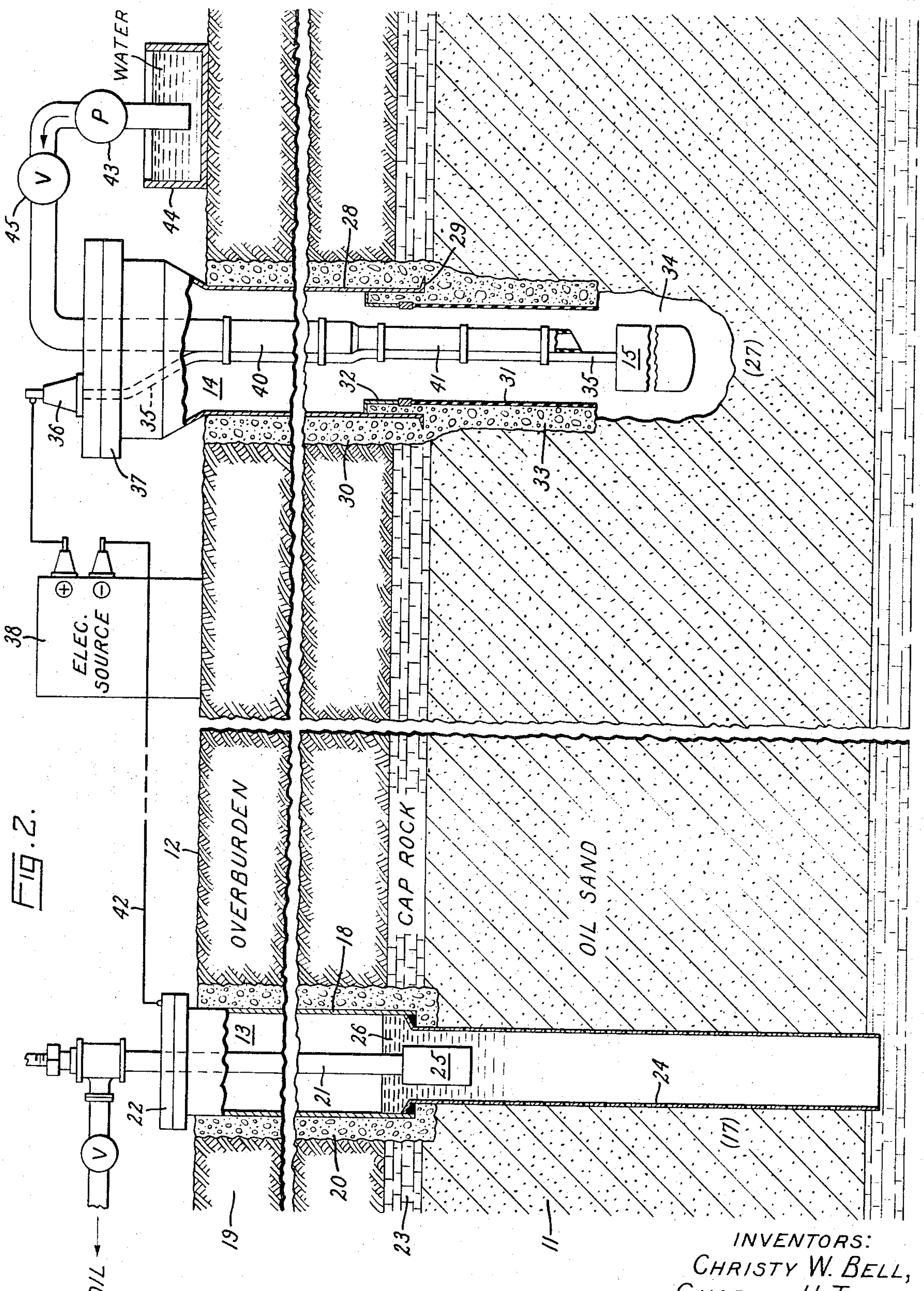

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Fig. 4.

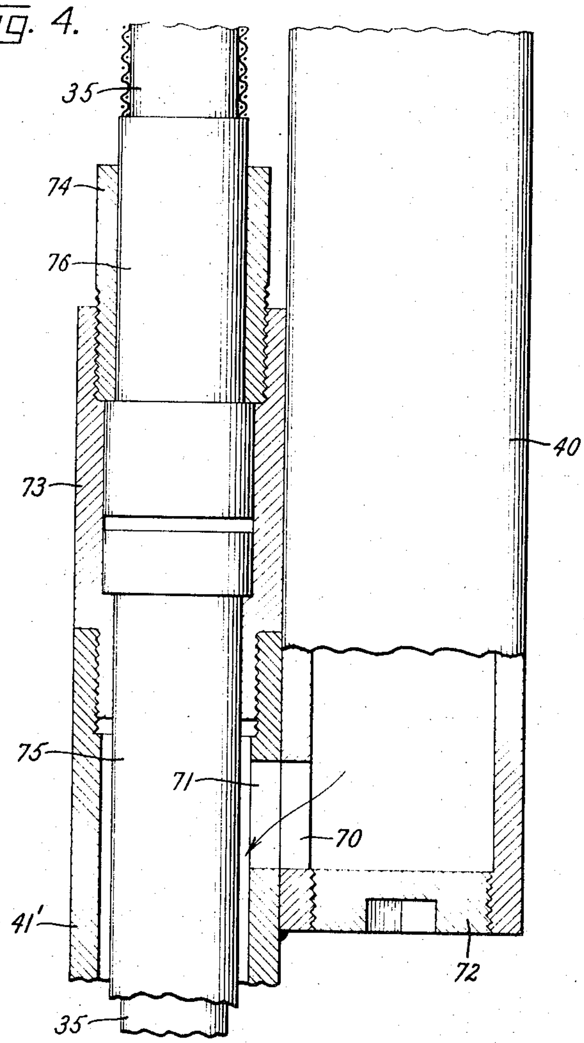

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Fig. 5.

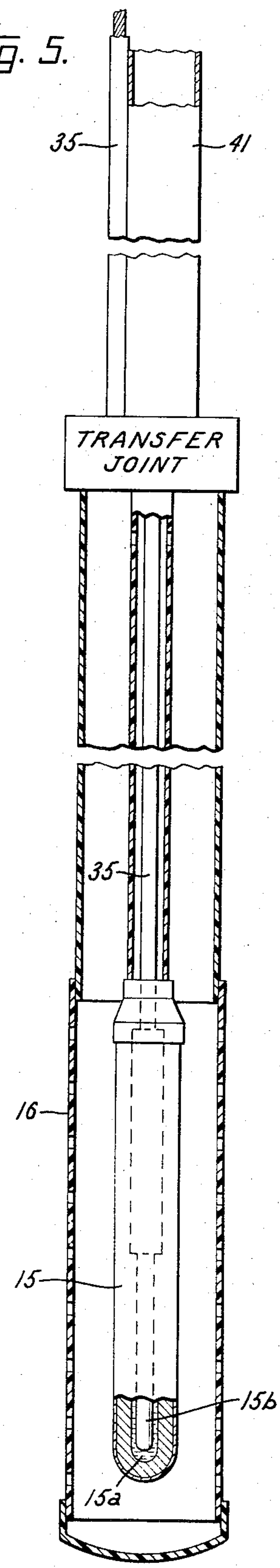
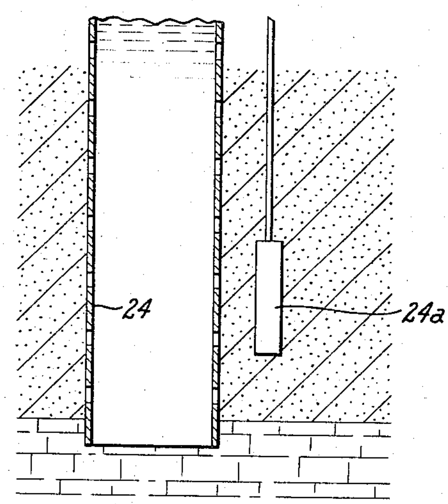


Fig. 6.



ELECTRO-THERMAL PROCESS FOR PROMOTING OIL RECOVERY

This application is a continuation-in-part of our U. S. Pat. application Ser. No. 88,854 filed on Nov. 12, 1970, and of our earlier original application Ser. No. 855,637 filed on Sept. 5, 1969, both now abandoned.

Our invention relates generally to the production of oil, and more particularly it relates to an improved method for recovering oil from subterranean oil reservoirs with the aid of electric power. The following published prior art is representative of that now known to applicants: U.S. Pat. Nos. 849,524–Baker; 1,372,743–Gardner; 1,784,214–Workman; 2,500,305–Ackerly; 2,795,279–Sarapuu; 2,799,641–Bell; 3,103,975-Hanson; 3,428,125–Parker; Annals of New York Academy of Science, Vol. 118, pages 585–602; French Pat. No. 1,268,588.

Crude oil is generally recovered from an oil-bearing earth formation initially as a result of gas or other formation pressure forcing the oil from the formation into a producing well which penetrates directly into the body of oil contained in the formation. As oil production continues, the initial reservoir energy is gradually spent and finally becomes insufficient to force the oil to the producing well. It is well known in the petroleum industry that a relatively small fraction of the oil in subterranean oil reservoirs is recovered during this primary stage of production; reservoirs containing highly vicous crude retain 90 per cent or more of the oil originally in place following primary production.

Numerous methods have been proposed for recovering more of the large amounts of oil remaining in oil-bearing formations following primary production. Generally such methods involve the expenditure of energy to supplement the expulsive forces and/or to reduce the retentive forces acting on the residual oil. While many of the prior art proposals are probably technically sound in theory, only a few have proved capable of yielding oil of sufficient value to justify the incremental costs of the apparatus required and the energy expended to produce it.

One secondary recovery technique that has been used with limited success involves injecting under pressure through one or more injection wells a scavenging fluid which displaces the oil from a reservoir through one or more spaced producing wells. Fluids which have been employed or suggested as a scavenging media in oil recovery operations include gases such as natural gas and compressed air and liquids such as water. Their temperature can be raised by means of down-hole electric heaters. Nevertheless, such methods are not markedly effective in recovering heavy viscous oil, probably because of the high capillary resistance to the flow of viscous oil through the interstices of the solid medium (usually sand) in the oil bearing formation.

More attractive methods for recovering viscous oil are ones involving heating a reservoir by steam and hot gases, thereby reducing the viscosity and specific gravity of the residual oil within the reservoir and rendering it more mobile. Hot gases may be generated by combustion processes conducted either outside or directly within the reservoir. Both of these thermal drive methods are characterized by low efficiency, and they have other recognized shortcomings. Steam-injecting methods, for example, are very slow.

Other prior art techniques for promoting 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 moving the oil by electroosmosis. The latter is described in U.S. Pat. No. 2,799,641 granted on July 16, 1957, to T. G. Bell who proposed placing two electrodes in contact with the oil at spaced apart locations in an oil bearing formation, whereby electromotive force could be impressed directly on the oil to cause electric current along the oil which consequently moves by electroosmosis toward the cathode. This result is premised on the theory that crude oil contains dissolved electrolytes and suspended charged particles which migrate through the pores and capillaries of the oil sands, dragging the oil molecules with them, under the influence of an electric field.

Much has already been published about the phenomenon of electroosmosis and its more common practical applications, such as dehydrating wet ground in the soil drainage art. Others have suggested applying the same principle to the water flooding method of oil recovery where it is intended to prevent clay swelling and thereby increase water injectivity. Heretofore, relatively low voltages (i.e., less than approximately 100 volts) and low power (i.e., less than approximately 10 kilowatts) have been recommended in the relevant literature. Insofar as we are presently aware, electroosmosis is not being used today in any large scale commercially operating oil field, in spite of an urgent need for improved secondary recovery methods.

In addition to the need for effective secondary recovery of oil in formations where natural pressure is depleted, there are known oil bearing formations so located that it is undesirable or inconvenient to drill a well directly into the containing body of oil. This may be, for example, in a body of oil which, whether or not under natural pressure, is located offshore or in some other location where local well penetration is difficult or undesirable. In such cases it is desirable to move the oil body through the formation to anoher location where a producing well is more feasible.

Accordingly, it is a general objective of our invention to provide improved means using electric power for stimulating and otherwise controlling the production of oil from oil-bearing formations.

It is a particular object of our invention to provide an improved method for utilizing unidirectional electric current of power magnitude to stimulate production of viscous oils in pressure-depleted earth formations.

Still another object of our invention is to provide a method for driving and directing oil in an earth formation from its natural position to a selected well position whether or not the well penetrates the body of oil directly or is positioned beyond it.

In carrying out our invention in one form, we suspend an anode in a cavity in an underground formation in at least a portion of which 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 is disposed at an approximately medial elevation of the region where the cavity is located. 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 hole 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 body of oil or be located beyond it so long as some or all of the oil body is located between the well and the anode cavity. While the anode hole and well bore may penetrate the body of oil to be recovered, either or both may penetrate the formation at a point beyond but near to the body of oil.

The cathode is located proximate the producing well and preferably it comprises a perforated metal liner in the bottom hole of the well bore. 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 electricity and formation water as the principal raw ingredients in a new electro-thermal method of stimulating 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 and to 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 unproductive wells may be vitalized in those situations where conventional recovery methods are difficult or impossible to practice because of the character of the oil-bearing formation (e.g., highly viscous tarsands, oil shale deposits, or "dead" oil fields). Our method can be successfully practiced even though initially there is no oil in the particular region or portion of the formation where the anode hole is located, so long as a reservoir of oil is present somewhere between anode and cathode. The oil normally will be extracted from the producing well, but it is possible to extract oil from the anode hole under some circumstances if that hole penetrates the oil body.

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 partial view of an alternative embodiment of the tubing string shown in the anode hole of FIG. **2**;

FIG. **5** is an elevational view, partly in cross section, of an anode assembly adapted for use in practicing our invention; and

FIG. **6** is a fragmentary cross sectional view of a modified cathode structure adapted for use in practicing our invention.

Referring now to FIG. **1**, the reference number **11** represents a subterranean reservoir containing crude oil and porous and substantially homogeneous media such as sandstone or limestone. Typically such oil bearing formations are found beneath the upper strata of earth, referred to generally as overburden, at a depth of the order of 1,000 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 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 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 separate electrode or to the metallic tubing in the producing well **13** 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**. Although the resistivity of oil is much higher than that of the overburden, anode-to-cathode current prefers to pass directly through the formation **11** because this path is so much shorter than any path through the overburden to "ground." 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 making the anode 15 relatively small and raising its potential with respect to the cathode to a suitably high voltage level, 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 and augmented by electroosmosis. Preferably we utilize an anode of relatively short length and diameter so that, while it provides sufficient surface area to conduct the required current at a desired current density per unit area, it will serve essentially as a point source of heat. We have found that for these purposes a diameter of several inches (i.e., 2 inches) and a length of several feet (i.e., 4 feet) is appropriate

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 oil reservoir 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.

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 or otherwise control 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 electrical 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 crossover means or coupler 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, for reasons explained hereinafter the liner 31 should have in practice 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., 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 and the anode may have a length of less than 10 feet. (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 exposed in operation to saline water and to oleaginous fluids in the surrounding earth formation. At the contemplated depth it is also exposed to high hydrostatic pressure. Under these conditions and when serving as a positive electrode to conduct unilateral current of large magnitude it is subject to electrolytic corrosion and to the development of local overheating by non-uniform distribution of current flow from its surface. To protect our anode from these effects and to ensure its operability at high current over substantial time periods of at least several months or more we utilize an anode assembly comprising a conductive anode body of elongate configuration mounted within a permeable concentric tubular enclosure radially spaced from the anode body. The enclosure cooperates with the anode body to protect it from contact with surrounding oil and sand and to ensure that its entire surface is constantly bathed in a cooling electrolytic fluid supplied through the tubing 41.

At FIG. 5 we have illustrated schematically an anode assembly designed to meet the stringent operating requirements referred to above. As shown at FIG. 5 the anode assembly comprises a hollow tubular anode body 15 electrically connected through its upper end to the conducting cable 35 and disposed concentrically in radially spaced relation within a permeable tubular enclosure 16 of insulating material. The anode 15 is preferably coated externally with a material, such as lead dioxide, which will effectively resist electrolytic oxidation and is provided internally with a recess partially filled with a conductive fluid, such as a body of mercury 15*a*. Electrical connection to the anode is made through a conductive stud or probe 15*b* connected to the cable 35 and extending into the mercury 15*a*. Preferably means (not shown) are provided to place the internal surfaces of the tubular anode 15 under a pressure substantially equal to the external pressure applied to the anode, thereby to preclude deformation and consequent mechanical damage to the anode.

The anode enclosure, or basket, 16 is closed at the bottom to provide a receptacle for sand or other foreign material entering from the surrounding earth formation. The major tubular portion is provided with a large number of small perforations or measuring orifices through which the saline electrolyte supplied through the pipe 41 may flow outwardly into the surrounding earth. By so regulating and restricting outward flow the electrolyte is constrained to flow over the entire anode surface to cool the surface and to ensure a substantially uniform current distribution over the surface. The small size of the perforations prevents ingress of oil and sand which, if allowed to deposite on the anode surface, would cause rapid erosion in localized areas of high current density. We prefer to form the insulating basket 16 of a highly heat resistant ceramic material, such as aluminum oxide, formed into a plurality of closely assembled annular rings or axial rods, or both, providing small apertures therebetween.

The anode structure and assembly shown in FIG. 5 and briefly described above is not the joint invention of the present applicants and is not claimed in this application, but is claimed and more fully described in a copending patent application Ser. No. 211,010, filed on Dec. 20, 1971 by C. H. Titus, H.N. Schneider and J.K. Wittle and assigned to the same assignee as the present application.

The anode 15 is attached to the lower end of the insulated cable 35, the other end of which emerges from a bushing or packing gland 36 in the cap 37 of the 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 (e.g., fiberglass), whereby there is no metal in the zone between the anode 15 and the casing shoe 29 except for the wires inside the insulated cable 35.

The negative pole (−) of the electric power source 38 is connected via a cable 42 to an exposed 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. 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 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., at least 1,000 p.s.i.) 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 extremely 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 adversely affecting the permeability of the formation. In oil fields where natural formation water is readily available, this water will usually be injected into the anode hole 14, thereby minimizing 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 injected water can also be treated if desired with chemical additives which have other beneficial effects 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 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 or controlling 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., at least 200 volts). Consequently current will flow through the formation 11 between the anode 15 and the producing well 13. The connate water in the interstices 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 per cent 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 advantageously 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 and the resistivity of the residual oil are reduced. After heating, the rate of water injection increases. 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.

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 electroosmosis. The latter effect can be attributed to a net movement of ions in the interstitial water under the influence of a unipolarity field. This electroosmosis motive force promotes a migration of heated water from the cavity **34** through the porous oil sand to the producing well **13.** In a given medium of volume flow of water due to electroosmosis 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 electroosmotic 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. Gases thus released, being compressible and under substantial pressure at the formation depth, apply additional pressure to the thermally fluidized oil and aid in driving it toward the cathode well. Some of the gases 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 under pressure 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.

At FIG. **6** we have shown by fragmentary and schematic illustration that the cathode electrode, here designated **24*a*,** may be discrete from the metal well liner **24** and located directly in the oil sand proximately adjacent the well liner. By so providing a separate or discrete cathode electrode it is possible to select its size and surface area relative to the size of the anode while maintaining the anode size within otherwise desirable limitations. The proportion of electric energy dissipated at the anode and cathode is dependent upon their relative surface areas, and a separate cathode electrode adds another degree of freedom in selecting a desired ratio. As the cathode is made smaller, or the anode larger, the relative amount of energy dissipated at the cathode increases. Thus by diminishing cathode surface area a significant amount of heat may be developed at the negative electrode so that this electrode acts as a secondary point source of heat. It is estimated that when using the well liner **24** as the cathode and the relatively small anode described above only about 5 percent of the electric energy will be dissipated at the cathode. It is possible that in some applications of our invention it may be desirable to increase cathode energy dissipation to 30 percent or more of the total. Increased heating in the cathode region will aid in lowering oil viscosity and facilitating flow in that region as well as in promoting hydrogenation of oil flowing into the producing well.

In the cavity **34** the 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, and therefore it may also be 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.

As 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 claimed in a copending patent application Ser. No. 116,035 filed on Feb. 17, 1971 by C. H. Titus and assigned to the same assignee as the present application.

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 mode 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 reversing polarity mode described in the preceding two paragraphs, respectively, it is possible to utilize pressure developed in the anode region to extract oil from that region **27** through the anode hole. 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 claimed in a copending patent application Ser. No. 117,488 filed on Feb. 22, 1971 by C. H. Titus and H. N. Schneider and assigned to the same assignee as the present application, now U.S. Pat. No. 3,674,912.

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 certain embodiments 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 improved electro-thermal method for stimulating oil recovery from a porous and substantially homogeneous underground oil bearing formation having at least two regions respectively penetrated by first and second spaced apart bore holes, comprising the steps of;

a. locating an electrode in the first bore hole at an approximately medial elevation of the proximate region of said formation, said electrode being sufficiently small to constitute effectively a point source of resistance heating;

b. immersing said electrode in a pressurized conductive liquid thereby to form an expanding body of liquid surrounding said electrode and constituting an electroconductive path between the electrode and the oil bearing formation;

c. applying unipolarity voltage between said electrode and an exposed conductor proximate the second bore hole, with the polarity of said electrode being positive relative to said conductor, the resulting unidirectional current through said porous formation having sufficiently high current 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

d. thereafter extracting oil from one of said bore holes.

2. The method of claim **1** wherein oil is extracted from said second borehole.

3. The method of claim **1** wherein said electrode comprises a relatively short cylindrical body, the length of said body being less than one-half the depth of said proximate region.

4. The method of claim **1** wherein the magnitude of the applied voltage is 200 volts or higher.

5. The method of claim **1** including the step of supplying electroconductive water through the first borehole to the vicinity of said electrode.

6. The method of claim **5** wherein said water is injected into said first borehole at a pressure sufficient to maintain the volume rate of flow of the injected water at a predetermined desired value.

7. The method of claim **5** including the step of applying sufficiently high voltage between said electrode and said conductor to heat the fluid in the vicinity of said electrode to substantially above 250° Fahrenheit.

8. The method of claim **7** wherein said fluid is supplied under sufficient pressure to maintain the heated fluid between the electrode and the oil-bearing formation in a liquid state.

9. The method of claim **1** wherein said exposed conductor comprises a metal liner in said second borehole.

10. The method of claim **1** wherein said exposed conductor is positioned in said formation proximately adjacent said second borehole.

11. An improved electro-thermal method of stimulating oil recovery from an underground oil-bearing formation that is penetrated by first and second spaced-apart boreholes, said first borehole having a casing whose lower end terminates near the top of the formation, comprising the steps of:

a. joining the upper end of a tubular liner of insulating material to the lower end of the casing in said first borehole;

b. suspending an electrode in a cavity in the formation below said liner;

c. injecting electroconductive fluid through said liner to said cavity;

d. applying unipolarity voltage between said electrode and a region of the oil bearing formation that is penetrated by the second borehole, with the polarity of the electrode being relatively positive; and

e. extracting oil from said second borehole.

12. The method of claim **11** including the step of disposing an insulated cable in said first borehole for connecting said electrode to the positive pole of a source of d-c electric power.

13. The method of claim **11** wherein said tubular liner has a relatively small inside diameter.

14. In an improved electro-thermal method for stimulating oil recovery from a porous and substantially homogeneous underground oil bearing formation that is penetrated by first and second bore holes each having a casing and a tubing string disposed therein, said bore holes communicating with horizontally spaced apart regions of said porous formation, the steps of:

a. introducing through the first bore hole and positioning at an approximately medial elevation in the corresponding region of said formation and electrode comprising an electroconductive body having a substantially noncorrodable surface, said electrode being sufficiently small to constitute effectively at point source of resistance heating;

b. supplying electroconductive liquid through the tubing string in the casing of said first bore hole to the vicinity of said electrode, said liquid forming an expanding body of liquid electrolyte in the porous formation surrounding said electrode;

c. electrically insulating said electrode from the casing of said first bore hole;

d. passing electric current through said liquid body and said formation between said electrode and the casing of said second bore hole, said current being sufficient to raise the temperature of said liquid body appreciably above the ambient temperature of said formation; and

e. withdrawing oil from the tubing string in the casing of said second bore hole.

15. The method of claim **14** in which said voltage is obtained from a d-c electric power source whose positive pole is connected by an insulated cable to said electrode.

16. An improved electro-thermal method for stimulating oil recovery from a porous and substantially homogeneous underground bearing formation comprising the steps of;

a. locating an electrode at an approximate medial elevation of a first region of said formation, said electrode being sufficiently small to constitute effectively a point source of resistance heating;

b. maintaining about and in contact with said electrode, by a process of regulated flow, a pressurized hydrous electrolyte of a composition having the essential characteristics of connate water present in said formation, said pressurized electrolyte forming an expanding body of liquid in the porous formation surrounding said electrode,

c. passing unidirectional current between said electrode and an exposed conductor located in another region of said formation, said other region being spaced from said first region and the polarity of said electrode being positive relative to said conductor , said current being sufficient to raise the temperature of said liquid body appreciably above the ambient temperature of said formation; and

d. extracting oil from one of said regions.

17. The method of claim **16** including the step of supplying said hydrous electrolyte through a borehole which penetrates said first region.

18. The method of claim **17** including the steps of regulating the supply of said hydrous electrolyte so that it flows at a volume rate which varies with the product of the magnitude of said applied voltage and the magnitude of electric current between said electrode and said conductor.

19. The method of claim **17** in which said hydrous electroltye is formation water.

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