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INITIATION OF COMBUSTION IN A SUBTERRANEAN FORMATION

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ABSTRACT OF THE DISCLOSURE

This specification discloses a process to be employed in the recovery by in situ combustion of hydrocarbon material from a subterranean formation. The process is directed toward the initiation of combustion and includes the steps of displacing hydrocarbons from the vicinity of the ignition well by passing into the formation a solvent which has mutual solubility for hydrocarbons and water, passing water into the formation, and thereafter initiating combustion. As a preliminary step, there is passed into the formation a hydrocarbon solvent in which the hydrocarbon material in the formation is soluble and which has a lower viscosity than the hydrocarbon material.

This invention relates to the recovery of hydrocarbon material from a subterranean formation and relates more particularly to the method of recovery of hydrocarbon material from a subterranean formation involving in situ combustion.

Precedures for the recovery of hydrocarbon material from a subterranean formation involving combustion of a portion of the hydrocarbon material within the formation are being used to a progressively greater extent in the petroleum industry. In these operations, which are commonly termed "in situ" combustion operations, an oxidizing fluid such as air is injected into the formation through one or more input, or injection, wells. The formation is provided with one or more outlet, or production, wells, and the oxidizing fluid flows through the formation in the direction of the outlet well or wells. Combustion of hydrocarbon material within the formation is initiated and with continued flow of oxidizing fluid through the formation a combustion front migrates through the formation. The migrating combustion front effects a displacement of hydrocarbon material from within the formation and the hydrocarbon material is recovered from the outlet well or wells.

Initiation of combustion of hydrocarbon material within the formation is effected at an ignition well which may be either an input well or an output well, depending upon the type of combustion operation being carried out. In the direct drive combustion operation, combustion is initiated within the formation adjacent an input well and the combustion front migrates through the formation in the same direction as the oxidizing fluid. In the reverse drive combustion operation, combustion is initiated within the formation adjacent an output well and the combustion front migrates through the formation in the opposite direction to the oxidizing fluid.

In both the direct drive and the reverse drive combustion operations, difficulties are encountered in the ignition well as a result of the high temperatures attained. The hydrocarbon material undergoing combustion at initiation may be contained within the formation directly adjacent the well and also within the well itself as a result of the material flowing into the well from the formation. On the other hand, the hydrocarbon material may be contained only within the formation directly adjacent the well. In both cases, combustion of the hydrocarbon material results in the attainment of a temperature within the well comparable to the temperature of combustion of the hydrocarbon material. As a result of the attainment of this high temperature, rapid deterioration and destruction of the well liner and other metal equipment in the well can occur. Additionally, sintering of earth material and other high temperature effects may occur within the formation in the immediate vicinity of the well. Since these effects occur in the immediate vicinity of the well, their adverse consequences on pressure drop conditions between the well and the formation are emphasized. Accordingly, difficulty thereafter occurs in obtaining a satisfactory rate of flow of oxidizing fluid into the formation from the input well where a direct drive combustion operation is carried out or flow of product from the formation into the output well where a reverse drive combustion operation is carried out. Further, in the direct drive combustion operation, the development of high temperatures in the formation in the vicinity of the input well may cause a bank of liquid hydrocarbon to form in the immediate vicinity of the well which further reduces the rate at which the oxidizing fluid may be passed from the well into the formation.

It is an object of this invention to provide a method for avoiding the attainment of undesirably high temperatures in a well leading to a subterranean formation wherein ignition of hydrocarbon material in the formation is to be initiated.

It is another object of this invention to minimize deterioration and destruction of metal equipment within a well leading to a subterranean formation wherein ignition of hydrocarbon material in the formation is to be initiated.

It is another object of this invention to provide a method for effecting initiation of combustion of hydrocarbon material within a subterranean formation at a well leading to the formation.

Other objects, and advantages, of the invention will become apparent from the following detailed description.

In accordance with the invention, initiation of combustion of hydrocarbon material within a subterranean formation penetrated by an ignition well is effected by a procedure involving firstly passing from the well into the formation a solvent which has mutual solubility for hydrocarbons and water; secondly, passing water into the formation from the well; and thirdly, effecting ignition of the hydrocarbon material within the formation in the presence of an oxidizing fluid passed into the formation.

In the procedure of the invention, the hydrocarbon material within the formation in the vicinity of the ignition well is displaced therefrom and moved back into the formation from the well. The solvent which has mutual solubility for hydrocarbons and water displaces the hydrocarbon material from the formation in the vicinity of the well and moves it inwardly from the well into the formation. Thereafter, the water displaces the solvent which has mutual solubility for hydrocarbons and water from the formation in the vicinity of the well and moves it inwardly from the well into the formation. The formation in the vicinity of the well is thus left free of combustible material. The term "combustible material" includes the hydrocarbon material within the formation, the solvent which has mutual solubility for hydrocarbons and water, and any other material in the formation capable of combustion. Movement of combustible material in the formation is effected to a sufficient distance from the ignition well that subsequent combustion of combustible material within the formation will not cause a rise in temperature at the well to result in untoward effects in the well. Accordingly, destruction of the metal equipment

within the well and sintering of earth material are minimized.

The solvent which has mutual solubility for hydrocarbons and water is capable of entering into solution with the hydrocarbon material in the formation. Upon entering into the formation from the well, the solvent forms a liquid phase within the formation consisting, at its leading edge adjacent the formation containing hydrocarbon material, of a solution of solvent and hydrocarbon material and, at its trailing edge, of solvent. The leading edge of the liquid phase is miscible with the hydrocarbon material within the formation and thus there will be no interface as a boundary between the hydrocarbon material and the solvent. Further, the solvent is miscible with the solution of solvent and hydrocarbon material and thus there will be no interface as a boundary between the solvent and the solution. Accordingly, as the solvent moves through the formation from the well, the hydrocarbon material will be stripped from the surfaces of the pore channels of the formation and will be replaced by the solution of the solvent and hydrocarbon material and the solution of the solvent and hydrocarbon material will, in turn, be replaced by the solvent. When the passage of solvent has been discontinued, the formation, beginning at the well and extending inwardly, will contain the liquid phase consisting of solvent, the leading edge of the liquid phase consisting of the solution of solvent and hydrocarbon material, and the hydrocarbon material.

Following passage of the solvent which has mutual solubility for hydrocarbons and water into the formation, the water is passed into the formation from the well. The water is capable of entering into solution with the solvent which has mutual solubility for hydrocarbons and water. Upon entering into the formation from the well, the water forms a liquid phase within the formation consisting, at its leading edge adjacent the formation containing solvent, of a solution of water and solvent and, at its trailing edge, water. The leading edge of this liquid phase is miscible with the solvent within the formation and thus there will be no interface as a boundary between the solvent and the water. Further, the water is miscible with the solution of water and solvent and thus there will be no interface as a boundary between the water and the solution. Accordingly, as the water moves through the formation from the well, the solvent will be stripped from the surfaces of the pore channels of the formation and will be replaced by the solution of water and solvent, and the solution of water and solvent will, in turn, be replaced by the water.

With continued passage of water into the formation, the formation, beginning at the well and extending inwardly, will contain the liquid phase consisting of water, the leading edge of this liquid phase consisting of a solution of water and solvent which has mutual solubility for hydrocarbons and water, the liquid phase consisting of the solvent which has mutual solubility for hydrocarbons and water, and the leading edge of this latter phase consisting of a solution of solvent and hydrocarbon material, and the hydrocarbon material. At first, there will be no interfaces existing as boundaries between the liquids. However, with continued passage of water into the formation, and depending upon the relative amounts of water and solvent, eventually an interface between the liquid phase consisting of water on the one hand and the hydrocarbon material in the formation on the other hand can appear due to dilution of the solvent by the water and consequent impairment of its ability to dissolve hydrocarbons.

Movement of combustible material into the formation should be effected for a distance of at least five feet radially from the wall of the ignition well. It has been found that, with movement of combustible material for this distance from the wall of the well, subsequent combustion within the formation will not cause a rise in temperature at the well to an undesirable extent. Accordingly, sufficient solvent which has mutual solubility for hydrocarbons and water, and sufficient water, are employed to move combustible material into the formation for a distance of at least five feet radially from the wall of the well. However, it is preferred that sufficient solvent, and water, be employed to move combustible material into the formation for a distance of at least ten feet radially from the wall of the well. However, greater quantities of solvent and water may be employed to effect movement of combustible material into the formation for a greater distance radially from the well, particularly where the formation is thick and has significant vertical permeability.

As stated, the hydrocarbon material within the formation is displaced and moved back into the formation from the well by the solvent which has mutual solubility for hydrocarbons and water. Satisfactory movement of the hydrocarbon material is effected where the amount of solvent employed is equivalent to the product of the porosity of the formation and the volume of an annulus having a thickness of at least one inch, but preferably of about four inches, and an internal radius of at least five feet plus the radius of the well. This amount thus provides a liquid phase within the formation consisting of solvent and solution of solvent and hydrocarbon material having a thickness of at least one inch at a distance of five feet from the wall of the well.

The amount of solvent passed into the formation will, thus, depend upon the distance radially from the well that the hydrocarbon material is to be removed and the thickness of the liquid phase. The amount of solvent passed into the formation will also depend upon the vertical thickness of the formation and the porosity of the formation. Thus, the amount of solvent to be employed can be given by the formula:

$$\pi[(R+D+t)^2-(R+D)^2]l\rho \qquad (1)$$

where

R is the radius of the ignition well,
D is the distance radially from the wall of the well that the hydrocarbon material is to be displaced,
t is the thickness of the liquid phase,
l is the vertical thickness of the formation, and
ρ is the porosity of the formation.

The amount of water employed should be at least sufficient to move the solvent which has mutual solubility for hydrocarbons and water to the desired distance from the wall of the well that the formation is to be left free of combustible material, i.e., at least five feet but preferably at least ten feet from the wall of the well. This amount will be equivalent to the product of the porosity of the formation and the volume of an annulus having a thickness of at least the distance that combustible material is to be moved into the formation. Thus, this amount can be given by the formula:

$$\pi[(R+D)^2-R^2]l\rho \qquad (2)$$

where R, D, l, and ρ have the definitions given above in connection with Formula 1. It will be understood that greater amounts of water can be employed. The use of greater amounts of water will move the solvent which has mutual solubility for hydrocarbons and water further into the formation from the well. This further movement of the solvent will also move the hydrocarbon material further into the formation as long as the solvent does not become so dilute with water that it is no longer miscible with hydrocarbons, i.e., an interface appears between the water and the hydrocarbon material.

Any type of solvent having mutual solubility for hydrocarbons and water may be employed. Solvents of this type are organic compounds. Solubility for hydrocarbons requires that the solvent contain a hydrocarbon group. Solubility for water requires that the solvent contain a polar group. Particular solvents which have been found to be useful include methyl alcohol, ethyl alcohol, propyl alcohol, isopropyl alcohol, n-butyl alcohol, isobutyl alcohol, tertiary butyl alcohol, 2-pentyl alcohol, tertiary

amyl alcohol, dichloro tertiary butyl alcohol, allyl alcohol, ethyene glycol, propylene glycol, diethylene glycol, butyl glycol, tetraethylene glycol, dipropylene glycol, tripropylene glycol, dioxane, ethylene glycol monomethyl ether, ethylene glycol monoethyl ether, ethylene glycol monopropyl ether, ethylene glycol monobutyl ether, ethylene glycol monophenyl ether, propylene glycol methyl ether, diethylene glycol n-butyl ether, dipropylene glycol monomethyl ether, tripropylene glycol monomethyl ether, ethylene glycol dimethyl ether, diethylene glycol dimethyl ether, triethylene glycol dimethyl ether, tetraethylene glycol dimethyl ether, triglycerol triacetate, methyl acetate, diethylene glycol monoethyl ether, methyl acetoacetate, acetone, methyl ethyl ketone, trichloro acetaldehyde (chloral), pyridine, and acrylaldehyde (acrolein). Of these solvents, it is preferred to employ isopropyl alcohol.

The water passed into the formation may be any water available. This water may be purified water, such as distilled water, water treated by ion exchange, or water otherwise treated to change the quantity or kind of dissolved constituents. On the other hand, where purified or treated water is unavailable, whatever water is available at the well site may be employed. This water may be surface water such as pond, lake, or river water, or may be ground water such as well or spring water. These waters will contain various dissolved constituents such as one or more of the metallic ions such as sodium, calcium, potassium, magnesium, silicon, aluminum, and iron and one or more of the nonmetallic ions such as chloride, sulfate, bicarbonate, nitrate, phosphate, borate, and sulfide. Sea water may also be used. The predominant dissolved material in sea water will be sodium chloride and the sodium chloride will be in a concentration of the order of 3 percent by weight. Filtration or other treatment of the water to remove solids may be employed.

Various petroleum-containing formations contain clay which has a tendency to swell when contacted with water. In the treatment of such a formation by the process of the invention, it is preferred to employ water containing a flocculant for clay. The flocculant may be any of those commonly employed for the treatment of clay such as those used in the treatment of clay in drilling fluids or in subterranean formations. The flocculant serves to decrease the swelling of the clay upon contact with water. A suitable flocculant is an electrolyte. Included among these electrolytes are sodium chloride, sodium sulfate, calcium chloride, calcium sulfate, magnesium chloride, and magnesium sulfate. Preferably, calcium chloride or sodium chloride is employed. Of course, where there is uncertainty as to whether a formation to be treated contains clay, a flocculant may be added to the water since the flocculant will have no adverse affect on the flow capacity of the formation to the hydrocarbon material or to its products formed by in-situ combustion. Where a flocculant is employed, it is preferred that it be employed in the amount of at least 1 percent by weight. However, greater amounts such as 2 or 3 percent by weight may be employed. Where water, such as sea water, or a surface, or a ground water, containing the electrolytes mentioned hereinabove is employed, a flocculant will have inherently been employed along with the water.

In a preferred embodiment of the invention, as a first step thereof, a hydrocarbon solvent in which the hydrocarbon material in the formation is soluble and which has a viscosity lower than that of the hydrocarbon material in the formation is passed into the formation. Thereafter, the solvent which has mutual solubility for hydrocarbons and water is passed into the formation. To the extent of the amount of the hydrocarbon solvent passed into the formation, the hydrocarbon material in the formation is dissolved by the hydrocarbon solvent and its viscosity is reduced. Further, the hydrocarbon material in the formation is, to the extent of the amount of hydrocarbon solvent employed, displaced by the hydrocarbon solvent and moved back into the formation from the well. The solution of hydrocarbon material with the hydrocarbon solvent, and the hydrocarbon solvent, will be less viscous than the hydrocarbon material and thus will be more readily displaced than the hydrocarbon material by the solvent which has mutual solubility for hydrocarbons and water. Thus, movement of the hydrocarbon material to the desired distance from the well by the solvent which has mutual solubility for hydrocarbons and water subsequently passed into the formation is more readily attained.

The hydrocarbon solvent employed may be any hydrocarbon solvent in which the hydrocarbon material in the formation is soluble and which has a lower viscosity than the hydrocarbon material. The nature of the hydrocarbon material in the formation will determine to some extent the nature of the hydrocarbon solvent employed. Where the hydrocarbon material is paraffinic in nature, it is preferred to employ a paraffinic hydrocarbon solvent. Thus, for paraffin hydrocarbon materials, natural gas liquids such as liquefied petroleum gas, liquid propane, and liquid butane, may be employed. Where the hydrocarbon material is asphaltic in nature, it is preferred to employ a hydrocarbon solvent which is predominantly aromatic in nature. By "predominantly aromatic in nature" is meant that the solvent contains, by weight, at least 50 percent of aromatic constituents. Predominantly aromatic solvents which may be employed include xylene, benzene, toluene, tetranaphthalene, and decahydronaphthalene. Satisfactory results may be obtained employing petroleum fractions, which may be refined petroleum fractions, containing aromatic constituents in amounts of at least 50 percent by weight. A particularly satisfactory refined petroleum fraction of this sort which may be employed is an Edeleanu sulfur dioxide extract of kerosine or diesel oil.

For any particular hydrocarbon material in the formation, selection of the hydrocarbon solvent to be employed may be made empirically. Thus, a sample of the hydrocarbon material from the formation may be treated with various solvents in order to determine the solvent which is satisfactory for use. On the other hand, the solvent may be selected on the basis of knowledge of the properties of the hydrocarbon material.

The amount of hydrocarbon solvent employed may be as desired. Regardless of the amount employed, solution and reduction in viscosity of at least a portion of the hydrocarbon material in the formation is obtained. Further, regardless of the amount employed, displacement and movement of hydrocarbon material in the formation back into the formation from the well to at least some extent is obtained. However, it is preferred to employ sufficient hydrocarbon solvent to move the hydrocarbon material into the formation for a distance of at least five feet, preferably at least ten feet, radially from the wall of the well. Satisfactory movement of the hydrocarbon material is effected where the amount of hydrocarbon solvent employed is equivalent to the product of the porosity of the formation and the volume of an annulus having a thickness of at least one inch, but preferably of at least four inches, and an internal radius of at least five feet plus the radius of the well. Greater amounts, of course, can be employed. The amount of hydrocarbon solvent employed can be given by Formula 1 set forth above in connection with the amount of solvent which has mutual solubility for hydrocarbons and water that can be employed.

In another embodiment of the invention, a surfactant is dissolved in one or each of the hydrocarbon solvent, the solvent which has mutual solubility for hydrocarbons and water, and the water. The presence of the surfactant lowers the interfacial tension between the liquid in which it is contained and whatever liquid phase this liquid contacts in the formation. As a result, the liquid containing

the surfactant is more readily able to move the liquid phase it contacts.

Any type of surfactant soluble in the liquid in which it is used may be employed. By surfactant is meant any compound which has the property of reducing the surface tension of the liquid in which it is dissolved and absorbing on the surface such as that of a solid or distributing itself at an interface between two liquid phases. Surfactants have a molecular structure containing a nonpolar group and a polar group. A nonpolar group will ordinarily be a hydocarbon group. The polar group will be hydrophilic. This characteristic of surfactants is shared with solvents which have mutual solubility for hydrocarbons and water. However, a surfactant may be distinguished from a solvent which has mutual solubility for hydrocarbons and water. The term surfactant is reserved for those compounds which, in small quantities, cause large decreases in interfacial tension between an aqueous phase and a hydrocarbon phase. An illustration may be made as follows. Consider a given family of organic compounds whose composition is changed by the addition of hydrophilic groups onto the molecule. The solubility of the resultant compounds varies from infinite solubility in hydrocarbons and zero solubility in water to zero solubility in hydrocarbons and infinite solubility in water. Generally, of these compounds of the same family, the most effective compound is the one that has the minimum total solubility in hydrocarbons and water. In other words, this compound is the one that concentrates itself mainly in the interface between the two phases.

The surfactant, as indicated, will be one which is soluble in the liquid in which it is employed. The surfactant employed in the solvent which has mutual solubility for hydrocarbons and water may be oil-soluble or water-soluble. The surfactant employed in the water will, of course, be water-soluble. The surfactant employed in the hydrocarbon solvent will be, in the main, oil-soluble. The surfactants may be nonionic, cationic, or anionic.

Water-soluble, nonionic surfactants which may be employed include the oxalkylene ethers of various alkyl, aryl, alkaryl, and aralkyl hydrocarbons. For example, there may be employed the oxyethylene or oxypropylene ethers of various hydrocarbons groups containing 6–15 carbon atoms. Other surfactants which may be employed include the partial esters of polyhydric alcohols with long chain carboxylic acids and esters of hydroxyalkyl ethers of polyhydric alcohols with long chain carboxylic acids. The long chain carboxylic acids are aliphatic carboxylic acids and contain between 12–18 carbon atoms. Particular compounds include glycerol mono-oleate, sorbitan mono-oleate, pentaerythritol mono-oleate, proylene glycol monostearate, glycerol monoricinoleate, sorbitol monopalmitate, the pentaerythritol ammono-ester of soybean fatty acids, sorbide monolaurate, glycerol monostearate, sorbitan trioleate, butylene glycol monolaurate and mannitan dilaurate.

Suitable oil-soluble surfactants include the sulfonates, sulfates, phenylic compounds, organic phosphorus compounds, phosphorus sulfide treated olefins, and metal soaps of carboxylic acids. Included among the sulfonates are the alkali metal and alkaline earth metal soaps of alkyl sulfonic acid, alkaryl sulfonic acid, and mahogany sulfonic acids. Other sulfonates which may be employed include mono- and poly-wax substituted naphthalene sulfonates, diphenyl ether sulfonates, naphthalene disulfide sulfonates, diphenyl amine sulfonates, dilauryl beta-naphthol sulfonates, dicapryl nitronaphthalene sulfonates, unsaturated paraffin wax sulfonates, hydroxy substituted paraffin wax sulfonates, tetraamylene sulfonates, mono- and poly - chloro substituted paraffin wax sulfonates, nitrosoparaffin wax sulfonates; cycloaliphatic sulfonates such as lauryl cyclohexyl sulfonates, mono- and poly-wax substituted cyclohexyl sulfonates.

The phenolic organic compounds which may be used as surfactants are the free oil-soluble phenolic compounds or their phenates. These compounds, to be suitably oil-soluble, should contain at least nine aliphatic carbon atoms. Specific examples are: 3,5,5-trimethyl - n - hexyl phenol, n-decyl phenols, cetyl phenols and nonyl phenols; alkaryl substituted phenols such as alkyl-phenyl phenols; polyhydroxy alkyl aromatic compounds such as 20-carbon alkyl resorcinol, or polyhydroxy alkyl benzenes, such as, for example, octyl catechol, and tri-isobutyl pyrogallol; monohydroxy alkyl naphthalenes such as 12-carbon alkyl alpha naphthol. Isoamyl or nonyl phenol disulfide and other alkyl substituted phenol sulfides containing at least 5-alkyl carbon atoms may be employed.

Useful organic phosphorus compounds include tri- and penta-valent organic phosphorus acids and the corresponding thiophosphorus acids and their oil-soluble salts, as, for example, phosphoric acids and thiophosphoric acids, phosphinic acids and thiophosphinic acids, and the like and the oil-soluble salts thereof. The organic radicals substituted may be aliphatic, cycloaliphatic, aromatic, substituted aromatic, and the like and preferably contain a total of at least about 12 carbon atoms. Suitable phosphoric acid compounds include, for example, monowax phosphorus acids, mono-octadecyl phosphorus acid, monododecyl phosphorus acid, methyl cyclohexyl phosphite, capryl phosphite, dicapryl phosphite, zinc monowax benzene phosphonate, zinc dodecyl benzene phosphonate, and the like. Useful organic thiophosphorus acids include dicapryl dithiophosphoric acids, dilauryl dithiophosphoric acids, di-(methyl cyclohexyl) dithiophosphorus acids, lauryl monothiophosphoric acids, diphenyl dithiophosphoric acids, ditolyl monothiophosphoric acids, di-(isopropyl phenyl) monothiophosphoric acids, and the oil-soluble salts thereof.

The phosphorus sulfide treated olefins and their oil-soluble metal salts which are suitable for use include those customarily used in lubricating oil formulations as corrosion inhibitors, and/or detergents. Specifically, they include potassium-polyisobutylenephosphorous sulfide products and a similar material containing no metal made by addition of a phosphorus sulfide to wax olefins. This latter material is made by first forming wax olefins from paraffin waxes by halogenation and dehydrohalogenation and subsequently treating the olefins with a phosphorus sulfide, preferably phosphorus pentasulfide.

Examples of specific soaps which may be employed include metal soaps of naphthenic acids and the higher fatty acids.

Suitable naphthenic acids include substituted cyclopentane mono- and di-carboxylic acids and cyclohexane mono- and di-carboxylic acids having at least about 15 carbon atoms for oil solubility, for example, cetyl cyclohexane carboxylic acids, dioctyl cyclopentane carboxylic acids; and dilauryl decahydronaphthalene carboxylic acids, and the like, and oil-soluble salts thereof.

Following passage of the water into the formation, ignition within the formation is effected. For this purpose, any of the procedures commonly employed for effecting ignition may be used. For example, ignition may be effected by placing an electric heater within the ignition well adjacent the formation and supplying electric energy to the heater whereby heat is conveyed into the formation. A gas-fired heater may be similarly employed. Simultaneously therewith, gas, which may be the air or other oxidizing fluid employed to maintain combustion, may be passed over the heater and passed into the formation to carry the heat from the heater to the portion of the formation interiorly from the well containing the hydrocarbon material. Similarly, charcoal or other combustible material may be positioned within the formation and, with supply of combustion supporting gas, ignited by suitable means. Where the hydrocarbon material in the formation is capable of spontaneous combustion upon passage through the formation of oxidizing fluid, ignition may be effected merely by passing oxidizing fluid into the formation. Upon attainment of ignition temperature and with supply of

oxidizing fluid, combustion will have been initiated within the formation and with continued supply of oxidizing fluid the combustion front will migrate through the formation.

Where the hydrocarbon material is sufficiently fluid to flow within the formation without the application of external energy, steps must be taken during ignition to prevent backflow to the well of the hydrocarbon material from the position to which it has been displaced. Where the direct cumbustion operation is employed, backflow of the hydrocarbon material is prevented by maintaining the oxidizing fluid at a sufficiently high pressure. Where the pressure of the oxidizing fluid within the well at the formation is 50 pounds per square inch, backflow of the liquid hydrocarbon material is ordinarily prevented. On the other hand, where the formation is under high pressure, higher pressures of oxidizing fluid may be required. The pressure of oxidizing fluid required to prevent backflow in direct combustion may be determined empirically either prior or subsequent to the passage of the hydrocarbon solvent where used, the solvent which has mutual solubility for hydrocarbons and water, or the water into the formation. For this determination, a suitable detector for liquid material in a well may be positioned within the well and fluid, such as the oxidizing fluid, passed into the formation. With hydrocarbon material in the well, the pressure of the fluid just below that which effects the beginning of movement of the hydrocarbon material from the well into the formation will be that which will prevent backflow of the hydrocarbon material.

The process of the invention may be applied to the recovery of any type of hydrocarbon material from a subterranean formation where in-situ combustion can be maintained. Thus, the process of the invention may be applied to the recovery of petroleum from a subterranean formation. It may also be applied to the recovery of tar from a tar sand formation. Situations may also be found where the process of the invention may be applied to the recovery of shale oil from a shale oil formation.

The following example will be more fully illustrative of the invention.

In a subterranean formation in California containing viscous petroleum, ignition was to be effected in order to recover the oil within the formation by direct in-situ combustion. The formation was provided with one input well and four output wells and the input well was provided with a liner and tubing. The diameter of the input well was six inches. The formation had a net thickness of 120 feet, and a porosity of 31.6 percent, and the top of the formation was at a depth of 2150 feet from the surface of the earth. As a first step in effecting ignition of the petroleum in the formation, 75 barrels of 42 gallons each of a hydrocarbon solvent were passed into the formation by passing the solvent down through the annulus between the liner and the tubing of the input well and through perforations in the liner to the formation. The hydrocarbon solvent was an Edeleanu extract of kerosene and diesel oil, having a gravity between 26° and 36° and containing 80 percent by weight of aromatic components. As a next step, 25½ barrels of isopropyl alcohol were passed into the formation. This was sufficient alcohol to provide a liquid phase having a thickness of at least one inch at about 6.9 feet radially from the wall of the well. Thereafter, 2000 barrels of water were injected into the formation. This water had its origin in a subterranean formation containing petroleum and was obtained by separation from a mixture of petroleum and water produced from the formation.

Air injection into the formation was begun immediately after the completion of the passage of the water into the formation. The air was injected at a pressure of 875 pounds gauge and this pressure was sufficiently high to insure that the formation oil did not backflow from the formation into the well. With continued injection of the air, the temperature within the formation began to increase and subsequently ignition of the formation occurred. Following initation of combustion in the formation, air injection was continued to drive the combustion front through the formation in the direction of the production wells. Successful injection of air was obtained. No difficulty was encountered with respect to maintaining the desired air pressure to effect passage of the air at the desired rate into the formation. Furthermore, there was no damage or deterioration of the liner or the tubing of the well by high temperatures.

Having thus described our invention, it will be understood that such description has been given by way of illustration and example and not by way of limitation, reference for the latter purpose being had to the appended claims.

We claim:

1. A process for initiating combustion within a subterranean formation containing hydrocarbon material and penetrated by an input means comprising at least one input well and output means comprising at least one output well, one of said wells being an ignition well, comprising:
   (a) passing into said formation through said ignition well a hydrocarbon solvent in which said hydrocarbon material is soluble and which has a viscosity lower than that of said hydrocarbon material whereby said hydrocarbon material is dissolved and its viscosity reduced and is displaced from the vicinity of said well,
   (b) passing into said formation through said well a solvent which has mutual solubility for hydrocarbons and water whereby said hydrocarbon solvent and said hydrocarbon material are displaced from the vicinity of said well,
   (c) passing into said formation through said well water whereby said solvent which has mutual solubility for hydrocarbons and water is displaced from the vicinity of said well, and
   (d) thereafter initiating combustion within said formation at said well in the presence of an oxidizing fluid.

2. The process of claim 1 wherein said solvent which has mutual solubility for hydrocarbons and water is passed into said formation in an amount sufficient to displace said hydrocarbon material from said formation for a distance of at least five feet radially from the wall of said well.

3. The process of claim 1 wherein said solvent which has mutual solubility for hydrocarbons and water is passed into said formation in an amount sufficient to displace said hydrocarbon material from said formation for a distance of at least ten feet radially from the wall of said well.

4. The process of claim 1 wherein said solvent which has mutual solubility for hydrocarbons and water is isopropyl alcohol.

5. The process of claim 1 wherein said oxidizing fluid is passed into said formation at a rate sufficiently high to prevent backflow of hydrocarbon material from said formation into said well.

6. The process of claim 1 wherein said solvent which has mutual solubility for hydrocarbons and water is passed into said formation in an amount given by the formula:

$$\pi[(R+D+t)^2-(R+D)^2]l\rho$$

where

R is the radius of said ignition well,
D is the radial distance that said hydrocarbon material is to be displaced from the wall of said well and is at least five feet,
t is the thickness of an annulus at a distance D from the wall of said well and is at least one inch,
l is the vertical thickness of said formation, and
ρ is the porosity of said formation.

7. The process of claim 1 wherein said hydrocarbon solvent is passed into said formation in an amount sufficient to displace said hydrocarbon material from said formation for a distance of at least five feet radially from the wall of said well.

8. The process of claim 1 wherein said hydrocarbon solvent is passed into said formation in an amount sufficient to displace said hydrocarbon material from said formation for a distance of at least ten feet radially from the wall of said well.

9. The process of claim 1 wherein said hydrocarbon solvent is passed into said formation in an amount given by the formula:

$$\pi[(R+D+t)^2-(R+D)^2]l\rho$$

where

R is the radius of said ignition well,
D is the radial distance that said hydrocarbon material is to be displaced from the wall of said well and is at least five feet,
t is the thickness of an annulus at a distance D from the wall of said well and is at least one inch,
l is the vertical thickness of said formation, and
ρ is the porosity of said formation.

10. The process of claim 1 wherein said hydrocarbon material is asphaltic and said hydrocarbon solvent contains at least 50 percent by weight of aromatic constituents.

11. The process of claim 10 wherein said hydrocarbon solvent is an Edeleanu extract of kerosine and diesel oil.

12. The process of claim 1 wherein said water is passed into said formation in an amount to displace said solvent which has mutual solubility for hydrocarbons and water from said formation for a distance of at least five feet radially from the wall of said well.

13. The process of claim 1 wherein said water is passed into said formation in an amount to displace said solvent which has mutual solubility for hydrocarbons and water from said formation for a distance of at least ten feet radially from the wall of said well.

14. The process of claim 1 wherein said water is passed into said formation in an amount given by the formula:

$$\pi[(R+D)^2-R^2]l\rho$$

where

R is the radius of said ignition well,
D is the radial distance that said hydrocarbon material is to be displaced from the wall of said well and is at least five feet,
l is the vertical thickness of said formation, and
ρ is the porosity of said formation.

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