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PROCESS FOR HEATING A SUBSURFACE FORMATION

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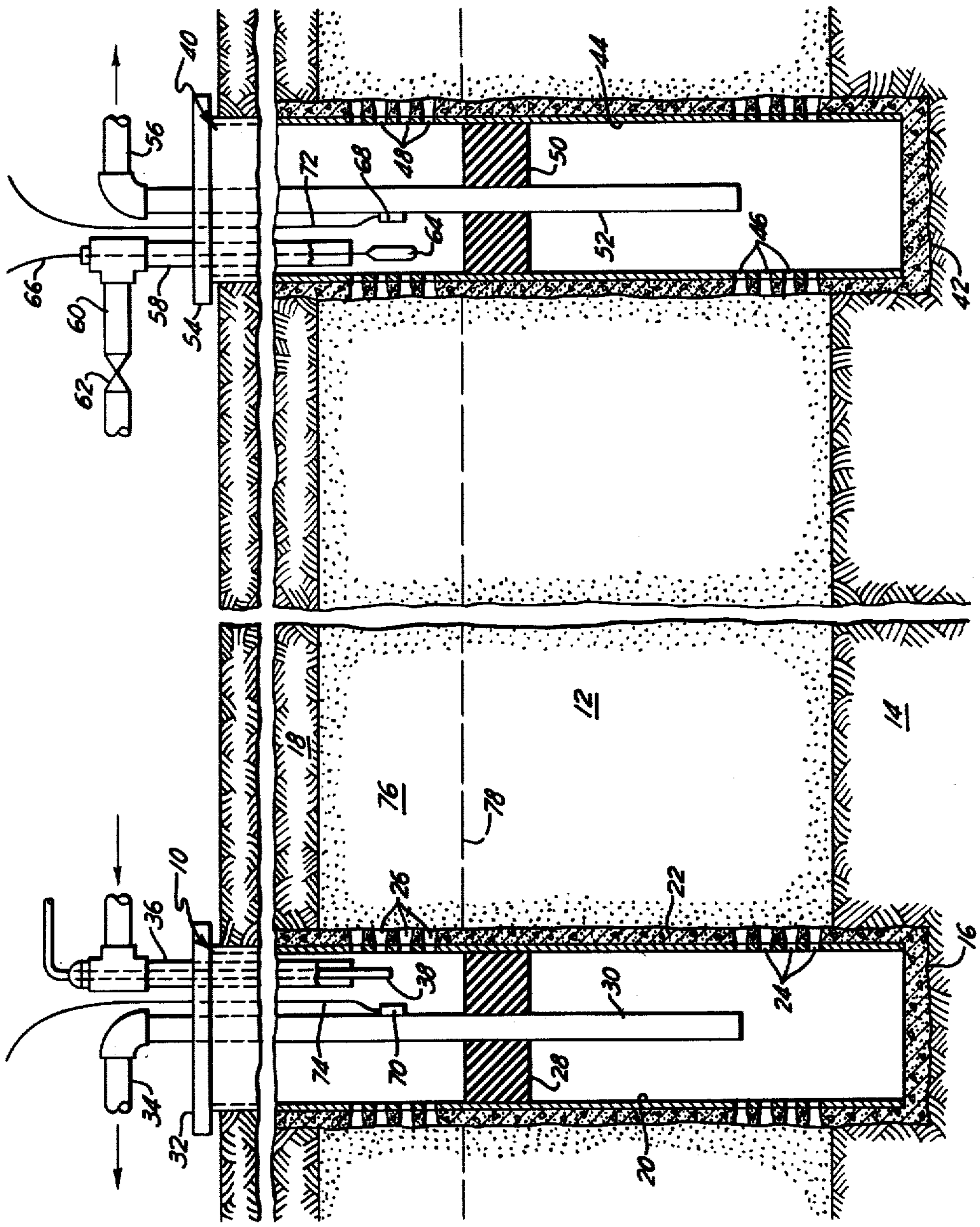

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PROCESS FOR HEATING A SUBSURFACE FORMATION

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This invention relates to the production of viscous crude oils and tar and more particularly to a method of heating such crude oil and tar while in the formation to facilitate their production.

There are many oil fields known to contain large amounts of oil that have not been recovered and that cannot be economically recovered by conventional production methods. In some of the fields the oil bearing sands have an extremely low permeability which prevents flow of the oil to the well at rates which justify continued operation of the well. In other oil fields the oil has such a high viscosity that acceptable production rates cannot be obtained even though the oil sands may have relatively high permeability. In some of these fields a portion of the oil may have been produced after initial completion of the well but loss of a portion of the pressure on the reservoir has caused the rate of production to decline rapidly. Ordinarily, the resistance to flow of the highly viscous crude oils is so great that secondary recovery operations designed to restore the pressure on the reservoir are not successful.

The viscosity of the highly viscous crude oils and tars can be greatly reduced by heating; however, effective heating of the oil in place in the formation is extremely difficult. The low thermal conductivity of the sands and the relatively long distances through which the heat must be transferred interfere with heating the oil by the usual techniques. Electric borehole heaters and fuel burners in the borehole are effective for only a short radial distance around the borehole and leave the major portion of the oil in the reservoir unheated. Attempts have been made to recover the viscous oils by in-situ combustion processes in which a portion of the oil is burned in place in the reservoir by the injection of an oxygen-containing gas into the reservoir. The large mass of cold oil between the production well and the combustion front interferes with flow through the pay zone and makes the usual in-situ combustion processes ineffective when the crude oil is highly viscous. Reverse burning in-situ combustion processes can be used in reservoirs where forward burning is unsatisfactory, but have the disadvantage of coking a substantial portion of the oil in place in the pay zone. Moreover, the permeability may be too low to sustain reverse combustion.

This invention resides in a method of heating highly viscous crude oils and tars in place in the reservoir by injecting into the reservoir a mixture of a fluid fuel and air at an injection well and burning the fuel in a channel through the reservoir. The gaseous products of combustion are discharged from the reservoir at a production well spaced from the injection well. The combustion front is made to travel back and forth between the production well and the injection well by controlling the fuel-air ratio injected into the reservoir. The combustion of the fuel is continued until the oil in the reservoir adjacent the channel in which the combustion occurs is heated by conduction to a temperature at which it can be produced economically.

The single FIGURE of the drawing is a diagrammatic illustration, partially in vertical section, of a preferred embodiment of this invention in which the combustion

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of the fuel takes place in the upper portion of the pay zone to heat the underlying oil.

It has been found that by control of the ratio of a fuel to air at the combustion front in a permeable formation, and the total injection rate, the direction of movement of the combustion front in the permeable formation can be controlled. In the following description, combustion in which the combustion front, fuel-air mixture, and combustion products move through the formation in the same direction is referred to as forward combustion or forward burning. Combustion in which the combustion front moves toward the injection well or zone and the fuel-air mixture and the combustion products move toward the production well or zone is designated reverse combustion or reverse burning. If the ratio of fuel to air at the combustion front is maintained above about 60 percent of the stoichiometric ratio, reverse burning occurs. If the ratio of fuel to air at the combustion front is reduced to below about 40 percent of the stoichiometric ratio, the burning will be converted to forward combustion. Although the forward combustion occurs at all fuel-air ratios below about 40 percent of the stoichiometric ratio that will support combustion, ordinarily little is gained by reducing the ratio below about 10 percent of the stoichiometric ratio.

If the fuel to air ratio is increased to extremely high ratios, for example, about 600 percent or higher of the stoichiometric ratio, the combustion will again be converted to forward combustion. Such extremely high ratios are generally out of the range of economic operation but may exist during the initial phases of combustion when hydrocarbons present in the reservoir are mixed in large quantities with gases injected for the heating processes. At intermediate ranges between about 40 percent and about 60 percent of the stoichiometric ratio, the type of burning, that is forward or reverse, will depend upon factors other than fuel-air ratio, such as the gas flux and the formation temperature. By gas flux is meant the volume of gas flowing per square foot of formation area per unit of time. However, the ranges above 60 percent of the stoichiometric ratio and below 40 percent of the stoichiometric ratio are broad enough to allow positive control of the direction of movement of the combustion front by control of the fuel-air ratio alone.

The heating process of this invention is particularly useful in aiding in the recovery of highly viscous crude oils. The process can be used in the initial recovery of oil from a reservoir or for the recovery of oil from partially depleted reservoirs. In the upper part of many reservoirs is a gas cap through which a gas can readily be displaced from one well to an adjacent well. Moreover, frequently in partially depleted reservoirs a permeable zone partially free of the viscous oil, which aids the injection and displacement of the fuel-air mixture from one well to an adjacent well, is formed across the top of a reservoir because of gravity segregation of oil in the reservoir. Even though the permeability of a formation to the viscous oils may be extremely low and preclude recovery of the oils without first heating the oil, the permeability of the formation to gas flow may be high enough for gas to thread its way from an injection well to a production well without displacing the oil from the reservoir. A large difference between the gas permeability and oil permeability is common when the oil is highly viscous. Moreover, the possible gain in production rate as a result of heating the oil is many times greater when the oils are initially highly viscous than when the oils are initially of low viscosity.

In the heating process of this invention an oxygen-containing gas is injected into the pay zone at one well called the injection well and products of combustion discharged at an adjacent well referred to as the production well. Throughout the description of the invention, the oxygen-containing gas will be referred to as air. It is to be understood that air enriched with oxygen or diluted with an inert gas can be used. In the initial stage of heating the formation, the pay zone may contain enough volatile hydrocarbons to form a combustible mixture when air alone is injected into the formation. If so, a preliminary heating can be obtained by injecting air alone at the injection well and igniting at the production well the combustible mixture resulting from the air mixing with volatile hydrocarbons in the pay zone. If the combustible mixture formed in the pay zone has a high enough concentration of hydrocarbons in it, reverse combustion will then proceed from the production well towards the injection well until the air has swept enough of the volatile hydrocarbons from the formation to reduce the fuel-air ratio to a range at which the burning is converted to forward burning and the combustion front then moves towards the production well. Reverse combustion can be continued after the ignition by injecting gradually increasing amounts of fuel at the injection well to maintain the desired fuel-air ratio at the combustion front.

In the description of the process of this invention, the first heating step is generally described as a reverse combustion step. If oil is produced during the heating phase, generally an initial reverse burning step is desirable to heat oil around the production well to facilitate its flow into that well for the full period of the heating process. However, the first step can be a forward burning step which is followed by a reverse burning step. In fact, if little oil is produced during the heating stage of the operation and the permeability of the formation to gases is high, it may be advantageous to use an initial forward burning step.

Forward combustion can be initiated by burning a fuel-air mixture in the borehole of the injection well for a period adequate to heat the surrounding formation to a temperature which will ignite a fuel-air mixture. Then the flow of fuel is reduced or stopped for a period. Upon resuming the flow of fuel, the fuel is ignited in the hot formation and the fuel-air ratio is adjusted to cause forward combustion to proceed.

In the first step of this process a mixture of a fluid fuel and air is injected into the pay zone at the injection well and displaced through the pay zone to an adjacent production well spaced from the injection well. If the permeability of the formation is low, it may be necessary to fracture the formation from the injection well to the production well to obtain a satisfactory rate of flow of the injected fuel-air mixture. A hydrocarbon gas is a preferred fuel because of its high heating value, the low resistance to flow through the pay zone, the east of mixing with an oxygen-containing gas, and its general availability in oil fields. The gaseous mixture is ignited at the production well by suitable means such as an electric spark and the injection of the fuel-air mixture continued. The concentration of the fuel in the fuel-air mixture is controlled to provide a fuel-air ratio of at least 60 percent of the stoichiometric ratio at the combustion front. Because some gases or oil will generally be picked up by the gaseous stream from the hydrocarbons present in the formation, the ratio of fuel to air in the injected gases may be lower than 60 percent of the stoichiometric ratio. The fuel picked up from the reservoir will then raise the fuel-air ratio to a ratio at which reverse combustion proceeds from the production well toward the injection well.

By measuring the temperature at the injection well, it can be ascertained when the combustion front has traveled from the production well to the vicinity of the injection well. The fuel to air ratio in the gas injected into the well is then lowered to below 40 percent of the stoichiometric ratio. The combustion in the reservoir is then converted to forward burning and the combustion front moves towards the production well. The concentration of the fuel in the gas injected into the formation is regulated to cause forward burning to proceed until the combustion front approaches the production well. If the oil adjacent the channel through the pay zone in which the combustion takes place is still too cold for effective production, the fuel to air ratio in the injected gases is then increased to convert the combustion to reverse burning and cause the combustion front to move back towards the injection well. The reversals of the direction of burning can be repeated as often as required to heat the oil in the formation to a temperature at which it can be produced at economical rates. The number of reversals of direction of movement of the combustion front will depend upon the initial viscosity of the oil and the porosity of the formation as well as an economic balance between the cost of heating and the value of the oil produced.

In a preferred embodiment of this invention, the fuel is burned in a channel across the top portion of the pay zone without burning an appreciable amount of oil. In this manner greater recoveries of the oil than are possible with the conventional in-situ combustion process can be obtained. The gravity segregation of the oil and gases in the pay zone aids the hot combustion products in bypassing the major portion of the oil as they travel from the injection well to the production well.

Referring to the drawing in which the preferred embodiment of this invention is illustrated, a well illustrated generally by reference numeral **10** is drilled through a pay zone **12** to a total depth **16** in a base rock formation **14** underlying the pay zone. A cap rock **18** overlies the pay zone **12**. Casing **20** is run into the well and cemented in place in accordance with the conventional well completion procedures. The casing **20** and the resultant cement sheath **22** surrounding the casing are perforated at **24** near the bottom of the pay zone **12** and at **26** at the top of the pay zone.

A packer **28** of a heat resistant material is set in the casing between the lower perforations **24** and upper perforations **26**. Production tubing **30**, which is open at its lower end, is run through the packer **28** to a position near the lower perforations **24**. The production tubing **30** extends to the well head and through a cap of suitable design, indicated by reference numeral **32**. Production tubing **30** is connected with a production line **34** for delivery of oil to suitable separation and storage equipment, not shown.

An air supply line **36** extends through the cap **32** and down the casing **20** to open in the annular space around the production tubing **30** above the packer **28**. Air supply line **36** is connected with suitable compressors, not shown. A gas feed line **38**, open at its lower end, extends down through the air supply line to a position adjacent the perforations **26**.

A production well indicated generally by reference numeral **40** spaced from the injection well **10** is drilled through the pay zone **12** to a total depth **42** in the base rock **14**. Casing **44** is set and cemented in place through the pay zone. The casing **44** is perforated near the bottom of the pay zone at **46** and near the top of the pay zone at **48** in a manner similar to injection well **10**. A packer **50** is set in the casing between the upper and lower perforations. Production tubing **52** is run through the packer **50** to open at its lower end adjacent the perforations **46**. Production tubing **52** extends upwardly through the casing to the well head and through a suitable closure at the well head, indicated by a plate **54** in the drawing. Production tubing **52** is connected with a line **56** for delivery of the product to separating and storage equipment, not shown.

A combustion products exhaust line **58** extends through the plate **54** and down the casing to open at its lower end near upper perforations **48**. Exhaust line **58** is connected to a suitable stack through a line **60** equipped with a valve 62 to allow control of the pressure in the annulus of the production well 40 above the packer 50.

Ignition of the fuel-air mixture in the production well is accomplished by means of a suitable igniter 64 connected through lead line 66 with a suitable source of electrical energy, not shown. A thermocouple 68 is positioned within the well 40 adjacent the perforations 48. A similar thermocouple 70 is installed in injection well 10. Lead lines 72 and 74 extend from thermocouples 68 and 70, respectively, to the well head of the production and injection wells where they are connected with means for indicating the temperature in the wells.

In the operation of the wells illustrated in the drawing air is injected into the formation through supply line 36 at the injection well. Simultaneously a fuel gas, such as natural gas, is injected through feed line 38. The gaseous mixture is displaced through the upper part 76 of pay zone 12 above the liquid level indicated by line 78 and then through perforations 48 into the production well 40 where it is ignited by igniter 64. The concentration of the fuel in the gaseous mixture is maintained above the minimum required for reverse combustion to cause the combustion front to move from the vicinity of production well 40 towards the injection well 10.

During early stages of the combustion the hydrocarbon gases present in the upper portion of the pay zone may be sufficient to give a fuel-air mixture sufficiently rich in fuel to cause reverse combustion to take place. After displacement of those gases, however, the fuel-air ratio in the mixture displaced into the formation at the injection well should be at least about 60 percent of the stoichiometric ratio. Injection of gas of that composition is continued until a temperature rise indicated by the thermocouple 70 shows that the combustion front is near the injection well. The fuel-air ratio in the mixture of gases injected at the injection well is then reduced to below about 40 percent of the stoichiometric ratio whereupon the combustion in the pay zone is converted to forward burning and the combustion front moves toward the production well. A sharp rise in the temperature indicated by thermocouple 68 will indicate that the combustion front is approaching the production well and the composition of the mixture injected at the injection well can again be changed to cause reversal in the direction of movement of the combustion front. The process is repeated with the combustion front traveling back and forth in the channel in the upper portion of the pay zone to heat the oil in place in the lower portion of the pay zone to a temperature which will reduce its viscosity to such an extent that production at satisfactory rates can be obtained. It is an important advantage of this invention that the combustion occurs in a relatively restricted channel through the pay zone thereby avoiding burning a substantial portion of the oil in place in the pay zone and allowing recovery of a large part of the oil.

After the oil is heated it can be produced by any of the conventional techniques. Gas can be injected into the top of the pay zone to increase the pressure on the reservoir and cause the hot oil of reduced viscosity to flow into the wells through which it is lifted to the surface. The oil in the pay zone may be heated sufficiently that no repressuring is necessary. The oil will flow by gravity into the wells through which it can be lifted to storage equipment at the well head. The process of this invention can also be effectively combined with a water flood operation. The greatly reduced viscosity of the hot oil in the reservoir allows it to be forced to production wells without requiring excessive pressure. When the heated oil is produced by gravity drainage from the formation, it is preferred to drain the hot oil into a substantially horizontal fracture of large capacity that has been formed in the lower part of the pay zone. The hot oil flows through the fracture to the well and is lifted to the surface.

The process of this invention was used in heating a heavy, highly viscous oil in a lease in Edmonson County,

Kentucky. The production well had been previously heated by means of a gas burner. Air was injected into an injection well at the rate of 300 standard cubic feet per minute. The gases were discharged from the formation into a production well 54 feet from the injection well. Reverse combustion was started by injecting propane at a rate equal to 50 percent of the stoichiometric equivalent of the air. The rate of air injection was continued at 300 cubic feet per minute. The combination of the residual fuel in the formation picked up by the air and the injected propane gave a fuel-air ratio causing reverse combustion to continue.

Twenty-four days later the rate of injection of propane into the formation at the injection well was reduced to 35 percent of the stoichiometric equivalent of the air injected. The rate of air injection was continued at 300 cubic feet per minute. Upon reduction of the rate at which the propane was injected into the formation the combustion was converted to forward combustion. Nine days later the rate of injection of air was increased to 580 standard cubic feet per minute and the rate of injection of the propane increased to maintain the fuel-air ratio at approximately 35 percent of the stoichiometric ratio. Forward burning in the formation continued.

If the concentration of the fuel in the mixture injected at the injection well is increased to many times the concentration corresponding to the stoichiometric concentration of fuel in a fuel-air mixture, the combustion may be converted from reverse combustion to forward combustion. A stainless steel combustion tube 3 feet long and about 3 inches in diameter was packed with a mixture of Baxterville crude oil and crushed Berea sandstone to give a porosity of about 40 percent and an oil saturation of about 60 percent. The tube was provided with electric heating elements and insulated to allow adiabatic conditions to be maintained. Thermocouples were installed at intervals along the length of the tube to allow observation of the direction of movement of the combustion front.

Combustion was started at one end of the tube by burning charcoal in a steady supply of air. Forward burning was allowed to continue over a distance of 21 inches from the inlet end of the tube. During the forward burning most of the oil was displaced from the tube while coke from the undisplaced oil was burned as a fuel. At this time a mixture of 14.2 percent by volume of normal butane (about 4½ times the stoichiometric concentration) and air was injected at a flux of 315 standard cubic feet per hour per square foot through the burned zone. The combustion in the tube was converted to reverse combustion which traveled at a velocity of about 5 feet per day.

The injected gas composition was next changed to 52.8 percent by volume normal butane (approximately 17 times the stoichiometric concentration) and the flux increased to 404 cubic feet per hour per square foot. The higher concentration of the fuel caused the combustion front to reverse the directon of travel and burn in a forward direction at a velocity of about 5 feet per day. The injected gas composition was then changed to 31.1 percent normal butane by volume and the flux increased to 687 cubic feet per hour per square foot. Forward burning continued at those conditions. Upon changing the gas composition back to its original value of 14.2 percent normal butane and a flux of 315 cubic feet per hour per square foot the combustion was converted back to reverse combustion.

In this invention the combustion front is made to move through the pay zone first in one direction and then the other by regulating the fuel-air ratio at the combustion front to change the combustion from reverse combustion to forward combustion, or vice-versa. By this process the combustion front may be made to make as many passes as desired in the pay zone by merely changing the fuel-air ratio from a range in which the combustion front moves in one direction to a range in which it moves in the other. If the air injected into the formation is enriched with oxygen, the direction of movement of the combustion front can be controlled by regulation of the ratio of fuel to the other gases injected into the formation but the limiting ratios will be lower than when the mixture consists only of the fuel and air. Similarly, a diluent inert gas may be added to the fuel-air mixture, in which event the limiting ratios of fuel to other gases will be increased.

Frequently, the portion of the pay zone traversed by the injected air will contain sufficient hydrocarbons that it will not be necessary to inject a fuel during the first pass of the combustion front through the formation. For example, in a pay zone which has been partially depleted and there has been a gravity drainage of oil from the upper portion of the pay zone, sufficient oil may adhere to the surfaces of the sands in the upper part of the formation through which the injected oxygen passes to supply the fuel for the initial pass of the combustion front. After the initial pass, the fuel-air ratio in the mixture injected into the pay zone is controlled to cause the combustion front to move in the desired direction in subsequent passes.

We claim:

1. A process for heating a subsurface formation containing oil penetrated by a first well and a second well spaced from the first well comprising injecting an injection mixture of a fuel gas and air into the formation at the first well and displacing it through a permeable channel in the formation to the second well, said injection mixture having a ratio of fuel to air adapted to form a fuel-air mixture at the second well having a fuel-air ratio at least sixty percent and less than about six hundred percent of the stoichiometric ratio, igniting the fuel-air mixture at the second well, containing the injection of the injection mixture at the first well to cause reverse combustion of the injected fuel to proceed from the second well toward the first well, and changing the composition of the injection mixture injected at the first well to a fuel-air ratio below about forty percent of the stoichiometric ratio to convert the combustion of the injected fuel to forward burning whereby the combustion front travels back and forth in the formation to heat oil in the formation.

2. A process for heating a subsurface formation containing oil penetrated by a first well and a second well spaced from the first well comprising injecting an injection mixture of a fuel gas and air into the formation at the first well and displacing it through a permeable channel in the formation to the second well, said injection mixture having a ratio of fuel to air to form a fuel-air mixture at the second well having a fuel-air ratio at least sixty percent and less than about six hundred percent of the stoichiometric ratio, igniting the fuel-air mixture at the second well, continuing the injection of the injection mixture at the first well to cause reverse combustion of the injected fuel to proceed from the second well toward the first well, changing the composition of the injection mixture injected at the first well to a fuel-air ratio below about forty percent of the stoichiometric ratio to convert the combustion of the injected fuel to forward burning and alternating the composition of the injection mixture injected at the first well from a fuel-air ratio below about forty percent of the stoichiometric ratio to a fuel-air ratio between sixty and six hundred percent of the stoichiometric ratio to change the direction of movement of the combustion front whereby the combustion front travels back and forth in the formation to heat oil in the formation.

3. A process for heating a subsurface formation containing oil penetrated by a first well and a second well spaced from the first well comprising injecting an injection mixture of a hydrocarbon fuel gas and air into the upper portion of the formation at the first well, displacing the injection mixture through the formation and withdrawing gases from the upper part of the formation at the second well whereby the injection mixture channels across the upper part of the formation, the composition of the injection mixture injected into the first well being controlled to form a fuel-air mixture at the second well having a ratio of fuel to air of at least 60 percent and less than about 600 percent of the stoichiometric ratio, igniting the fuel-air mixture at the second well, continuing the injection of the injection mixture at the first well to cause reverse combustion of the injected fuel to proceed from the second well toward the first well, and changing the composition of the injection mixture injected at the first well to a fuel-air ratio below about 40 percent of the stoichiometric ratio to convert the combustion of the injected fuel to forward burning whereby the combustion front travels back and forth in the formation to heat oil in the formation.

4. A process at set forth in claim 3 in which the formation is a partially depleted formation.

5. A process as set forth in claim 3 in which the oil level in the formation is below the level at which the injection mixture is injected into the formation.

6. A process for producing oil from a subsurface formation containing a viscous oil penetrated by a first well and a second well spaced from the first well comprising injecting a gaseous injection mixture of fluid fuel and air into the formation at the first well and displacing it through a permeable channel in the formation to the second well, said injection mixture having a ratio of fuel to air to form a fuel-air mixture at the second well at least sixty percent and less than about six hundred percent of the stoichiometric ratio, igniting the fuel-air mixture at the second well, continuing the injection of the injection mixture at the first well to cause reverse combustion of the injected fuel to proceed from the second well toward the first well, changing the composition of the injection mixture injected at the first well to a fuel-air ratio below about forty percent of the stoichiometric ratio to convert the combustion of the injected fuel to forward burning whereby the combustion front travels back and forth in the formation to heat oil in the formation, thereafter injecting fluid into the formation from one of said first and second wells to displace the heated oil to the other of said first and second wells, and delivering the oil through said other well to the surface.

7. A process for heating a subsurface formation containing oil penetrated by a first well and a second well spaced from the first well comprising forming a fracture in the formation extending between the first well and second well, injecting a gaseous injection mixture of a fuel and air having a fuel to air ratio higher than 60 percent and less than about 600 percent of the stoichiometric ratio into the fracture at the first well, and displacing the injection mixture through the fracture to the second well, igniting the fuel-air mixture discharged from the fracture at the second well whereby reverse burning of the injected fuel proceeds from the second well toward the first well, changing the composition of the injection mixture injected at the first well to a fuel-air ratio below about 40 percent of the stoichiometric ratio whereby the direction of burning in the fracture is changed to cause forward burning of the injected fuel to proceed toward the second well, and alternating the composition of the fuel-air mixture between a fuel-air ratio less than 40 percent of the stoichiometric ratio and a fuel-air ratio between 60 and about 600 percent of the stoichiometric ratio to cause periodic reversal of the direction of travel of the combustion front in the fracture.

8. A process for heating a subsurface formation containing oil, said formation being penetrated by a first well and a second well spaced from the first well, comprising injecting a gaseous injection mixture of a fluid fuel and air into the formation at the first well and displacing it through a permeable channel in the formation to the second well, the injection mixture of fluid fuel and air having a ratio of fuel to air at least 60 percent and less than about

600 percent of the stoichiometric ratio, igniting the mixture at the second well, continuing the injection of the mixture at the first well to cause reverse combustion of the injected fuel to proceed from the second well toward the first well, and changing the composition of the injection mixture injected at the first well to form a mixture having a fuel-air ratio less than 40 percent of the stoichiometric ratio causing forward combustion in the formation whereby the combustion front is made to travel first in one direction and then the other to heat oil in the formation.

9. A process for producing a viscous oil from a subsurface formation penetrated by a first well and a second well spaced from the first well, comprising forming a fracture from at least one of the wells extending therefrom through the lower portion of the formation, injecting a gaseous injection mixture of a fluid fuel and air from the first well into a permeable channel across the upper portion of the formation and displacing the injection mixture through the formation to the second well, said injection mixture having a ratio of fuel to air at least 60 percent and less than 600 percent of the stoichiometric ratio to cause reverse combustion in the formation when ignited, igniting fuel discharged thereinto at the second well, continuing the injection of the injection mixture of fuel and air at the first well to cause reverse combustion of the injected fuel to proceed toward the first well, changing the composition of the mixture injected at the first well to form a mixture at the combustion front having a fuel to air ratio less than 40 percent of the stoichiometric ratio to cause forward burning of the injected fuel in the formation, alternating the composition of the injection mixture between a fuel-air ratio of 40 percent of the stoichiometric ratio and 60 to 600 percent of the stoichiometric ratio whereby the combustion front reverses its direction of movement in the formation to heat oil therein, draining hot oil from the formation into the fracture, and lifting the oil through the well communicating with the fracture to the surface.

10. A process for heating a formation containing a hydrocarbon oil and producing the oil therefrom, said formation being penetrated by an injection well and a production well spaced from the injection well, comprising fracturing the formation from the injection well, injecting a gaseous injection mixture of a fluid fuel and air into the fracture and displacing it therethrough to the production well, said injection mixture having a ratio of fuel to air to form a fuel-air mixture having a fuel-air ratio at the production well at least 60 percent and less than

about 600 percent of the stoichiometric ratio, igniting the fuel air mixture at the production well, continuing the injection of the injection mixture at the injection well to cause reverse combustion of the injected fuel to proceed through the fracture toward the injection well, changing the composition of the injection mixture injected at the injection well to a fuel-air ratio below about 40 percent of the stoichiometric ratio to convert the combustion of the injected fuel to forward burning in the fracture whereby the combustion front travels back and forth in the fracture to heat oil in the formation, and recovering oil through said production well.

11. A process for heating a subsurface formation having a permeable channel across the top thereof and penetrated by an injection well and a production well comprising heating the formation adjacent the injection well to a temperature which will ignite a fuel-air mixture, displacing a gaseous injection mixture of a hydrocarbon fuel and air having a fuel-air ratio less than 40 percent of the stoichiometric ratio from the injection well into the permeable channel whereby forward burning of the injected fuel is initiated, continuing the injection of the injection mixture to displace said mixture toward the injection well through the permeable channel in the formation, and thereafter changing the composition of the injection mixture to a fuel-air ratio higher than 60 percent and less than about 600 percent of the stoichiometric ratio whereby the combustion of the injected fuel is converted to reverse combustion and the direction of movement of the combustion front is reversed.

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