

Nov. 29, 1960

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2,962,095

UNDERGROUND COMBUSTION PROCESS FOR OIL RECOVERY

Filed March 6, 1957

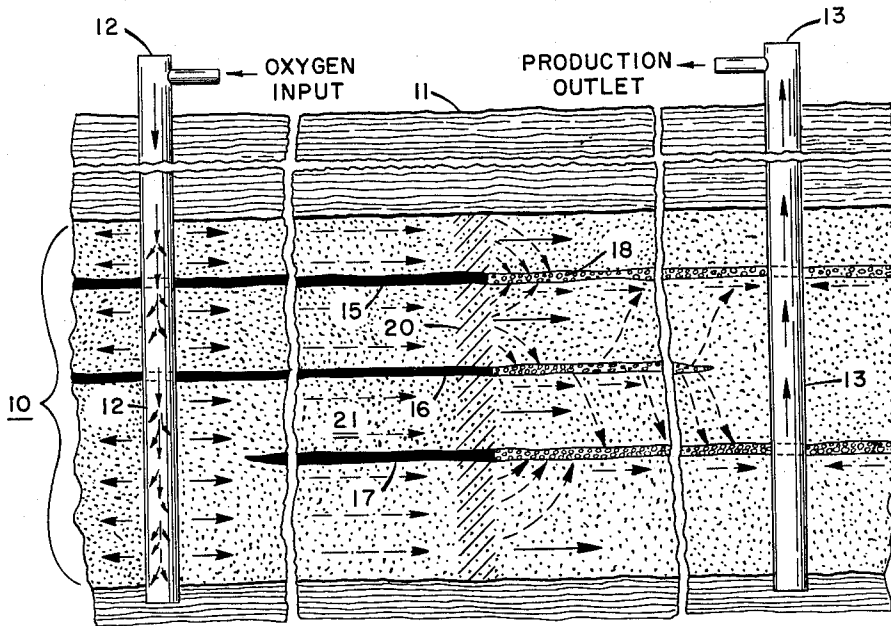


FIG. 1

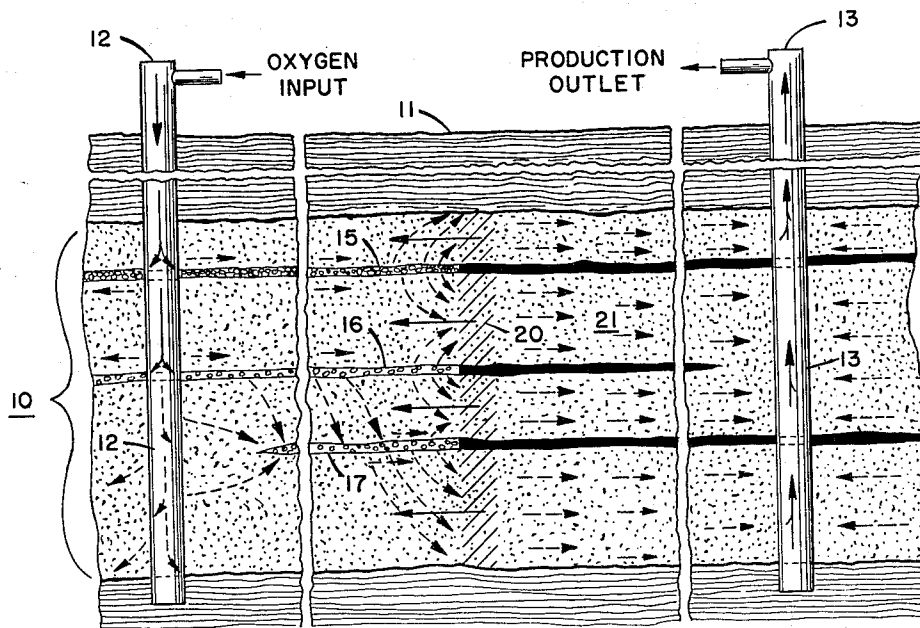


FIG. 2

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## UNDERGROUND COMBUSTION PROCESS FOR OIL RECOVERY

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Filed Mar. 6, 1957, Ser. No. 644,383

4 Claims. (Cl. 166—11)

This invention relates to the recovery of oil from sub-surface formations and is directed to processes of oil recovery which utilize combustion within the reservoir for generating heat and otherwise assisting in the displacement and recovery of the oil. More specifically, the invention is directed to extending the use of such processes to reservoirs of low permeability or shallow depth, but it is by no means limited thereto.

It has heretofore been considered that oil-recovery processes utilizing combustion are for the most part limited to use in reservoirs of greater than 50 or 100 millidarcys permeability and at depths which are greater than 1,000 or 1,500 feet. In shallower formations of lower permeability, it has appeared that the pressures necessary to achieve flow rates for proper and satisfactory operation of the combustion process are often higher than the formation can withstand. Even in deeper formations, the cost of providing and operating injection equipment for high-pressure operations tends to make the processes uneconomic.

The absolute permeability of rock material is, of course, a function of the rock structure. It is well-known, however, that the apparent or effective permeability of porous rocks is substantially reduced when oil, gas, and water flow through them simultaneously. Such three-phase flow conditions may occur quite readily in combustion recovery operations due to the high temperature associated with the combustion, which is frequently high enough to vaporize substantially all of the in-place liquids, some of which may subsequently condense.

While it has been proposed to increase the flow capacity of the producing formation by fracturing it, the combustion under such conditions will generally be confined to the fractures. The rise in temperature in the formation between the fractures may then be insufficient to displace the oil, so that large volumes of oil in place may be bypassed and not recovered.

It is, accordingly, a primary object of my invention to provide an improved method or process of utilizing underground combustion for oil recovery which is applicable to formations of substantially any permeability and depth below the ground surface, but which is especially useful in low-permeability formations or those at shallow depths. Another object is to provide such a combustion recovery method wherein the pressure differentials accompanying flow through the formation are substantially reduced by fracturing, but wherein the tendency to bypass the oil in place is substantially eliminated. A further object of the invention is to provide a recovery process utilizing combustion, in which process advantage is taken of the increased flow capacity of fractures in the formation, but in which the combustion itself is caused to take place principally within the formation rather than in the fractures. Other and further objects, uses, and advantages of the invention will become apparent as the description proceeds.

Briefly stated, the foregoing and other objects are accomplished by providing spaced wells penetrating the for-

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mation and initially hydraulically fracturing the formation with horizontal fractures extending all or a substantial part of the way between the wells at proper vertical levels within the formation. During fracturing there is introduced into the fractures and deposited therein a material to maintain the fractures open and permeable until the arrival of a combustion zone, when the material will then be affected by the combustion or its associated temperature rise to reduce the fracture permeability substantially or to seal it completely. This material is preferably a rigid, granular solid capable of acting as a support or prop to hold the fracture open, but susceptible to being altered, softened, or consumed by the combustion or the heat thereof to have its compressive strength or supporting ability destroyed so that the fracture closes itself or becomes sealed by the softening and flow of the introduced material.

After the fractures have been thus formed and the granular material deposited therein, a combustion zone is initiated within the formation and is propagated there-through by injecting combustion-supporting, oxygen-containing gas through the input well to the combustion zone within the formation. Ahead of the propagating combustion zone in the direction of its propagation, the flow of fluids is primarily along the fractures, while behind the combustion zone or after it has passed, the fractures are substantially sealed and the flow of fluids is through the burned-out formation.

Ordinarily, the recovery operations in which such temporarily supported fractures are used may be characterized as "forward" combustion operations, in which the flow of fluids between the input and the producing wells and the propagation of the combustion zone take place in the same direction. The open fractures ahead of the combustion zone accordingly then provide a relatively low-resistance path for the flow of combustion products and displaced formation liquids. Thus, even though three-phase flow may take place, the resultant or effective permeability is scarcely affected, as it is a characteristic of fracture permeability to remain nearly constant for multi-phase flow.

Behind the combustion zone the closed or sealed fractures in the burned-out area force the combustion-supporting oxygen or air to flow primarily through the formations to the combustion zone therein between the fractures. Due to the substantially complete removal of the in-place liquids from the burned-out zone, however, the pressure drop in this portion of the air flow path is substantially reduced. Thus, the presence of the fractures ahead of the advancing combustion zone effectively reduces the pressure differential to values which the formation can safely withstand even though it may lie at a shallow depth. Since by far the major part portion of the fluid-carrying capacity of the formation for three-phase flow is provided by these fractures, the absolute permeability of the formation itself becomes of secondary importance.

Such forwardly propagating combustion processes however, are not the only ones which may utilize this invention, however, as there may be occasions in combustion with "reverse propagation" where fracturing and depositing heat-sensitive materials can be used to reduce materially the flow resistance. By "reverse propagation" combustion is meant those processes in which the direction of propagation of the combustion zone is opposite to the flow of fluids through the formation. In other words, while the fluids move generally through the formation from the input toward the output well, the combustion zone goes in the opposite or reverse direction and thus backs up through the formation from the output well toward the input well where the combustion-supporting gases enter.

In such combustion operations, the closed fractures behind the propagating combustion front force the fluids to be recovered to flow through the formation, but the large pressure drop of three-phase flow is largely avoided because the heat deposited in the burned-out zone maintains most or all of the normally liquid formation fluids in the vapor state. Even if there is some condensate or unvaporized liquid present in this zone, its viscosity is so low at the elevated temperature that the increase in pressure drop is small compared to what it would be at the normal reservoir temperature. On the other side of the combustion zone, the cool combustion-supporting input gases flow from the input well primarily by the low-resistance path of the fractures, but upon approaching the location of the combustion zone where the fractures are closed or sealed, the input gases are forced out into the main body of the formation where the combustion reaction then takes place. Thus, the fractures effectively reduce the pressure drop and increase the formation flow capacity for a given input pressure, while closing or sealing of the fractures by the granular agent prevents bypassing of oil in place by too rapid reverse propagation of the combustion through only the fractures.

This will be better understood by reference to the accompanying drawings forming a part of this application and showing diagrammatically the operation of typical embodiments of the invention. In these drawings,

Figure 1 is a diagrammatic representation of a cross-section of a producing stratum with a forward combustion process utilizing the invention in operation therein; and,

Figure 2 is a diagrammatic illustration similar to Figure 1, showing the use of the invention in a reverse-propagation combustion process.

Referring now to these drawings in detail and particularly to Figure 1, portions of the earth's surface and subsurface are shown diagrammatically in vertical cross-section and include an oil-bearing stratum 10. From the earth's surface 11 at least two wells penetrate the stratum 10 at a suitable spacing, the well 12, for example, being equipped as an input well, while the well 13 is equipped as an output or producing well. These wells are shown only diagrammatically on the drawing, but it will be understood that the equipment not shown in detail may be that conventionally employed and connected in the ordinary manner, both wells having one or more strings of casing or tubing suitably cemented or supported in place, the well 12 being connected to a conventional supply of oxygen or air under pressure, and the well 13 being connected to apparatus for separating gas and liquid and storing the recovered liquids. As all of this equipment may be entirely conventional and no particular types are required in this invention, no detailed showing is deemed necessary.

Before any combustion is initiated within the formation 10, one or more horizontal fractures are created in the formation between the wells 12 and 13. These fractures may be initiated in and extended from either or both of the wells 12 and 13, either continuously or completely between the wells as shown by the fracture 15, or only a substantial part of the distance between the wells, as is shown by fractures 16 and 17. As the vertical location, the initiation, and the extension of these fractures can be accomplished as desired by means and procedures well known in the hydraulic-fracturing art, and as no special adaptation of these processes is involved in this invention, further detailed description on the point is deemed unnecessary.

Generally speaking, when fractures are formed and extended by hydraulic fracturing methods, they are normally filled or held open by depositing therein a solid granular medium which has a substantial compressive strength and is highly permeable to fluid flow. The most commonly used material is graded sand.

In accordance with the present invention the fractures

15, 16, and 17 are maintained open and permeable by depositing in them a granular agent 18 which, like sand, has good compressive strength and permeability at ordinary reservoir temperatures but, unlike sand, loses these properties at the moderately elevated temperatures, in the range from about 500° to 1000° F., which are most often characteristic of combustion zones in underground formations. The loss of compressive strength of granular material 18 may occur in any of several ways such as softening and flow under pressure, melting, decomposition, or even by combustion.

Once these requirements are understood, it will be immediately apparent that any of a great number of materials may be used as the granular agent 18 in this invention. One class of such materials is hard, organic materials which will be decomposed or consumed by the combustion. As examples of such organic materials may be mentioned ground hard fruit stones, nutshells, synthetic or natural resins or plastics, and the like. These are preferably formed or ground to approximately uniform sizes which are neither very large nor very small, a size corresponding to a screen size between about 8 and about 40-mesh being preferred. The more nearly uniform in size the particles are within this range the greater is the permeability of the fracture that is filled with them. It is also highly desirable that the shape of the particles be rounded so as to be cylindrical or spherical, and when manufactured particles are employed such shapes can be easily provided.

Besides organic materials, there may be mentioned also mineral materials either natural or manufactured, such as low melting-point glasses, or minerals such as stibnite, anglesite, or chalcopryite, all of which melt, soften, or decompose at temperatures substantially lower than the sand which is conventionally used as the fracture-packing agent. Another desirable attribute of the granular particles materials is that they should possess good supporting strength combined with low density, in addition to the moderate or low softening or melting temperature. As materials possessing these properties in high degree there may be mentioned certain light metals and metal alloys in the form of pellets, beads, or particles, such as aluminum, magnesium, or their alloys with other metals. Such materials, which tend to yield elastically and deform under the pressure imposed on them by the walls of a fracture of the fracture-creating pressures have been removed, are to be preferred to those which are brittle and tend to shatter under the applied stresses of the fracture walls such as crystalline materials, and some of the hard, organic materials. It is often observed that the small particles formed by fragmentation of larger particles of brittle materials tend to close the fracture and block the permeability. Therefore, non-shattering metal beads or pellets are thus able to provide the forces necessary to support or hold open the fracture walls without contributing small particles to block the pore spaces between the pellets. Although complete melting of the particles may not occur in the 500°-1000° F. range, substantial softening does take place.

With the fractures in the formation 10 thus formed and held open by the packing of granular material 18, combustion is initiated at the bore of the input well 12 in any suitable manner. For example, the walls of the well bore within the formation 10 are preheated by an electric heater or a gas-fired heating device to a temperature above the ignition temperature of the formation hydrocarbons. Thereafter, the injection of an oxygen-containing gas stream into the input well 12 from the ground surface is begun, and combustion of the oil in place starts and propagates outwardly from the well 12 through the formation 10.

Figure 1 shows diagrammatically the conditions which exist within the stratum 10 after the combustion zone 20 has propagated for some distance away from the well 12 toward the well 13. In the burned-out zone 21 ex-

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tending completely around well 12 out to the position of the zone or combustion front 20, the granular material 18 within the fractures has been affected by the combustion to allow the closing or otherwise substantial sealing of the fractures 15, 16, and 17, as is indicated by the solid shading. The flow of the input gas stream is thus forced to take place relatively uniformly throughout the burned-out zone 21, as is indicated by the dashed-line arrows. The resistance to this flow of oxygen-containing gases, or the resultant pressure drop, is, however, substantially reduced compared to what it would be in the original formation, since substantially all of the in-place liquids have been consumed or displaced, and the input oxygen or air flows as a single phase.

Ahead of or downstream from the combustion front 20 the fluids, both liquid and gas, enter the fractures 15, 16, and 17, which remain open and thus have a very large conductivity compared to the formation itself. Even though the flow in these fractures is three-phase flow, the pressure differentials are about the same as for single-phase flow and are small compared to what they would be through the formation in the absence of the fractures. Where a fracture, such as 16, terminates short of the bore of output well 13, the fluids may be required to migrate through the formation to another fracture such as 15 or 17 which does communicate with the well 13; but even in such a path the flow resistance is low compared to that through the formations without fractures.

As an example of the operation of this embodiment of the invention, assume that the wells 12 and 13 are located 330 feet apart in a five-spot pattern. The input well 12 is at the center of a square, while the output well 13 is one of four such wells at the four corners of the square. Suppose that the formation 10 is 20 feet in thickness, has a permeability of 10 millidarcys as measured on a dry core with air flow, a porosity of 20 percent, and a saturation of 50 percent of 30° A.P.I. gravity oil. With these and other conditions specified, comparable pressure drops can be determined without and with fractures in the formation.

At the time when combustion front 20 has propagated half-way from input well 12 to output well 13, while moving at the rate of 0.2 foot per day, an injection of air of about 1 million cubic feet per day measured under standard conditions of temperature and pressure is required. The pressure drop of this volume of air flow in the burned-out zone 21 with fractures absent or sealed is about 100 pounds per square inch. About 120 barrels per day of liquids comprising displaced oil, water, and condensate flow to the four output wells, one-fourth of this being to well 13.

Downstream from the combustion front 20 the pressure drop of these liquids plus the gaseous products of combustion will, without fractures, be about 3600 pounds per square inch. Added to the pressure drop in the burned-out zone 21, a total applied pressure of about 3700 pounds per square inch above the existing reservoir pressure is required just to overcome the resistance to flow. Thus the reservoir must be located at a depth of at least about 4000 feet and preferably at a substantially greater depth, as otherwise it may not be able to withstand the applied pressure at the well 12 without erratic fracturing of the formation in such ways as to allow bypassing of large volumes of oil in place. Also, the investment and operating costs of equipment for providing such pressures will be high enough to make the process uneconomic in many or perhaps most instances.

With fractures present, the situation becomes entirely different. The 100 pounds per square inch pressure drop of the air flow in the burned-out zone 21 will of course remain the same, as the fractures will have been sealed by the medium 18 in this zone. The great difference is in the flow of liquids and gases ahead of the combustion zone 20. Only a reasonable number of fractures with an average fluid-carrying capacity of fractures common

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in the art are required to increase the fluid conductivity of this portion of the formation from 200 to 1000 millidarcy feet. This conductivity is so much larger than without the fractures that the fluid-carrying capacity of the formations can be neglected to a first approximation and all of the fluid considered to be flowing in the fractures. The 120 barrels per day of produced oil and connate and condensed water, together with the gaseous products of combustion, then will have a maximum pressure drop of only about 700 pounds per square inch, which with the pressure drop of the air in the burned-out zone 21 makes a total of only about 800 pounds per square inch pressure drop. Thus, a producing horizon of the foregoing characteristics at only 900 feet depth can safely withstand the application of such pressures, and the investment and operating cost of the compression equipment are correspondingly less.

The forward-propagation process of underground combustion for oil recovery which has been described is not the only type of underground combustion recovery operation in which my invention can be utilized, as a description of Figure 2 will make clear. This latter figure illustrates a basically different type of underground combustion recovery process, wherein the conditions of fluid flow are quite unlike those in the process illustrated by Figure 1. As in that figure, the flow of fluids through the reservoir stratum 10 is away from the input well 12 toward the producing well 13. The propagation of the combustion zone 20 however, is exactly opposite to this, away from the producing well 13 and toward the input well 12. This basic process of reverse-propagation combustion is more fully described and claimed in my co-pending application Serial Number 445,133, filed July 22, 1954.

In carrying out this process and utilizing the present invention, the fractures 15, 16, and 17, are formed and packed with combustion-sensitive granular materials 18 as in Figure 1. It will be understood that the reservoir stratum 10, particularly as modified by the presence of fractures 15, 16, and 17, is relatively gas-permeable without appreciable displacement of the in-place liquids. After the fractures have been formed and packed, a combustion zone or front 20 is initiated at the bore of the output well 13, for example, by preheating the formation face exposed therein to a temperature above the ignition temperature level of the in-place oil, and the combustion so initiated is then supported by injecting oxygen-containing gas into well 12 to travel through the formation 10, and particularly the fractures 15, 16, and 17 therein, to the front 20. Heat is then generated by the combustion of part of the in-place oil with this oxygen at the front, while that part of the in-place liquids which is not consumed by the combustion (which uses up all of the input oxygen) is vaporized and/or cracked by the heat generated in the combustion zone and thereafter flows primarily as a gas or vapor to the output well bore 13. From there it is taken to the ground surface to be cooled, condensed, and the valuable products recovered.

As soon as the fractures 15, 16, and 17, are exposed to the heat of the combustion zone 20, the material 18 in the fractures is affected by the combustion temperature in such a way as to allow closing or sealing of the fracture. Accordingly, downstream from the combustion zone 20 in the direction of output well 13 the flow of fluids takes place substantially entirely through the formations. The closing of the fractures at the combustion zone 20 causes the input oxygen arriving near the combustion zone through the fractures to diverge therefrom out into the formation matrix and there produce the desired combustion. This flow of air or oxygen takes place as suggested by the dotted-line arrows to the left of the combustion zone 20 in Figure 2. The combustion zone 20 propagates according to the direction indicated by the solid-line arrows of this figure.

Although the closing of the fractures downstream from

the combustion front 20 causes the fluids to be recovered through the formation rather than by flowing along the fractures, the flow resistance under these conditions is much smaller than it would otherwise be because substantially all of these fluids are in the vapor state and thus constitute a single phase. As the burned-out zone 21 through which the combustion front 20 has passed in this manner remains at an elevated temperature, except for loss of heat by conduction to the rocks above and below the reservoir stratum 10, fluids vaporized at the combustion zone itself tend to remain in the vapor state. Due to the elevated temperature throughout the burned-out zone 21, however, even though some of the highest-boiling liquids may not be vaporized, their viscosity is so greatly lowered by the degree of heating provided that they flow through the formation with a relatively small pressure drop.

Upstream in the direction of flow, to the left of the combustion zone 20 in Figure 2, the travel of the input oxygen-carrying gas is primarily through the open fractures 15, 16, and 17, instead of through the body formation 10, where the in-place liquids would substantially prevent flow due to the presence of two or possibly three flow phases, assuming connate water is present in quantity as is true of many formations. The presence of the fractures 15, 16, and 17, being open in this portion of the formation 10, however, so increases the gas permeability of the formation that the input oxygen-carrying gases tend to channel through these fractures and thus bypass the in-place liquids in the formation. In other words, these fractures provide precisely the channeling effect that is desired here but which is normally to be avoided at all costs in conventional recovery methods by gas repressuring or the like where gas displacement of the in-place liquids with greatest efficiency is desired.

Thus, it will be apparent that, even in the operation of underground combustion processes other than the forward-combustion processes wherein the flow of fluids and propagation of the combustion zone take place in the same direction, the presence of fractures which become sealed by the heat or chemical reactions of the combustion front is advantageous for reducing the overall pressure drop of the fluids between the input and output wells. Such pressure-drop reduction as is provided by the open fractures is frequently sufficient to make an otherwise uneconomical process economically feasible, or to make recovery from a shallow-depth or low-permeability reservoir possible where it would otherwise be impossible.

While my invention has been explained in detail with reference to the foregoing specific embodiments thereof, it is to be understood that still further modifications and details will be apparent to those skilled in the reservoir-engineering art. The invention therefore should not be considered as limited to the details set forth, but its scope is properly to be ascertained from the appended claims.

I claim:

1. The method of oil recovery from an underground oil-producing stratum which is penetrated by two spaced wells of similar depth respectively adapted for use as an input well and as a producing well, which method comprises the steps of hydraulically fracturing said formation to create fractures which extend horizontally through said formation for a substantial part of the distance between said wells, depositing in said fractures a granular material, substantially all of said material having a substantial compressive strength at normal reservoir temperatures and substantially zero compressive strength at temperatures substantially above said normal temperatures but less than about 1000° F., initiating a combustion front within said stratum at the bore of one of said wells, injecting an oxygen-containing gas through said input well to flow horizontally to said front and maintain said combustion, and to cause said front to propagate horizontally through said stratum, displace the oil in place therein, and drive it toward said output well, said horizontally propagating front progressively acting on said granular material to destroy its compressive strength and progressively cause said fractures to become substantially sealed, whereby the flow of fluids takes place with substantially reduced pressure drop primarily through said fractures in the unburned portion of said stratum and primarily through said stratum in the burned-out portion thereof between said wells, and recovering oil from the fluids emerging from said producing well.

2. The method of claim 1 wherein said fracturing step comprises creating at least one fracture which extends continuously between said wells.

3. The method of claim 1 wherein said initiating step comprises initiating a combustion front at the bore of said input well so that substantially horizontal propagation occurs in the same direction as the fluid flow from said input to said output well, and the flow of displaced liquids ahead of said front is primarily along said fractures.

4. The method of claim 1 wherein said initiating step comprises initiating a combustion front at the bore of said output well so that substantially horizontal propagation occurs in the opposite direction to the fluid flow, the flow of oxygen-containing gas from said input well being primarily along said fractures, and the flow of displaced fluids from said front to said producing well is primarily through said stratum and in the vapor phase.

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