Jan. 21, 1969 J. D. ALEXANDER ETAL 3,422,891

RAPID BREAKTHROUGH IN SITU COMBUSTION PROCESS

Filed Aug. 15, 1966

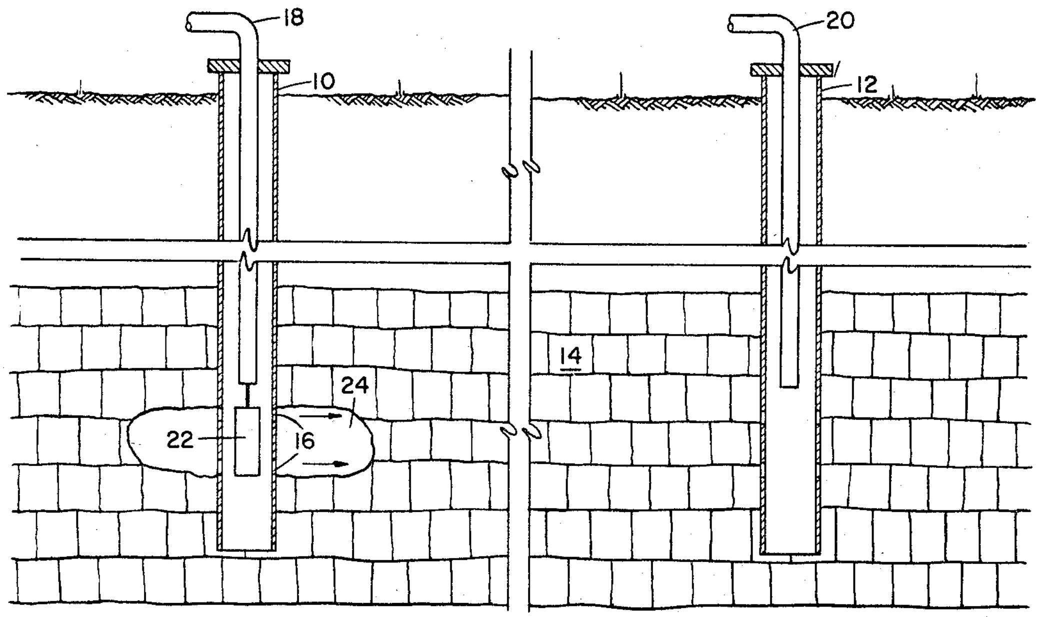

FIG. 1

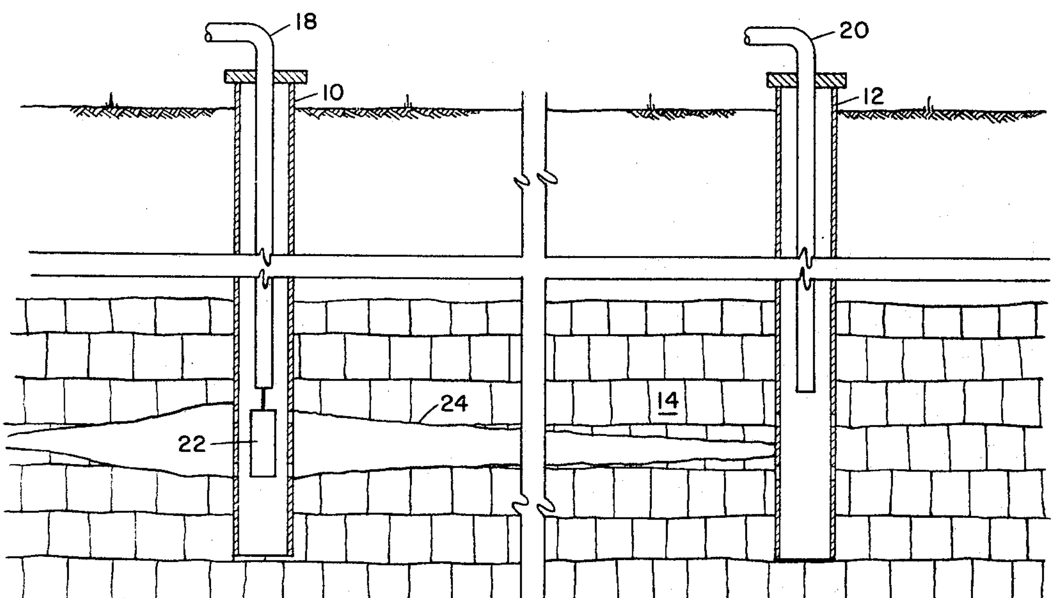

FIG. 2

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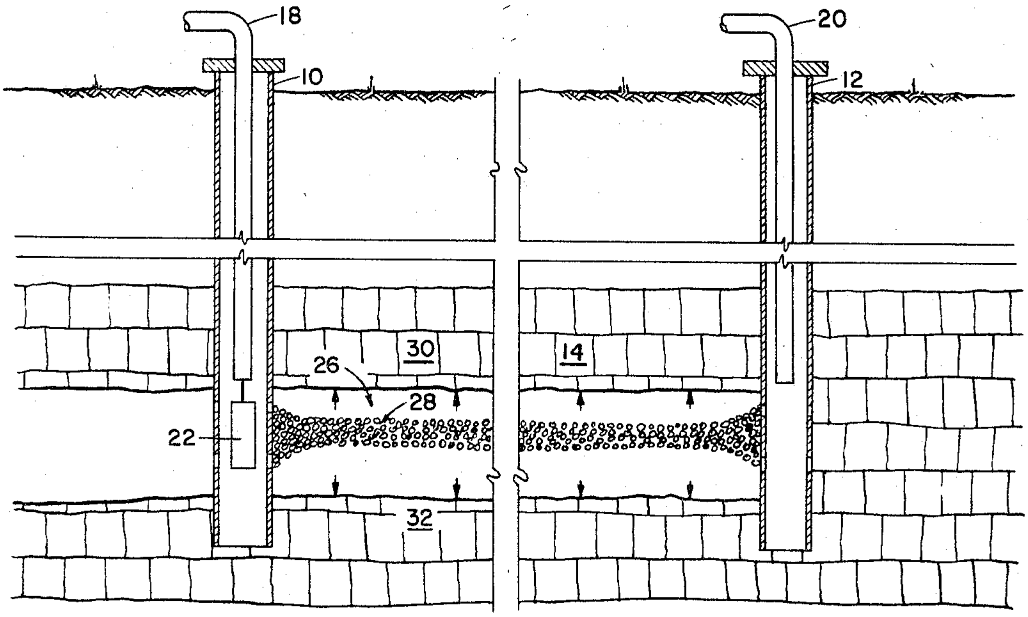

FIG. 3

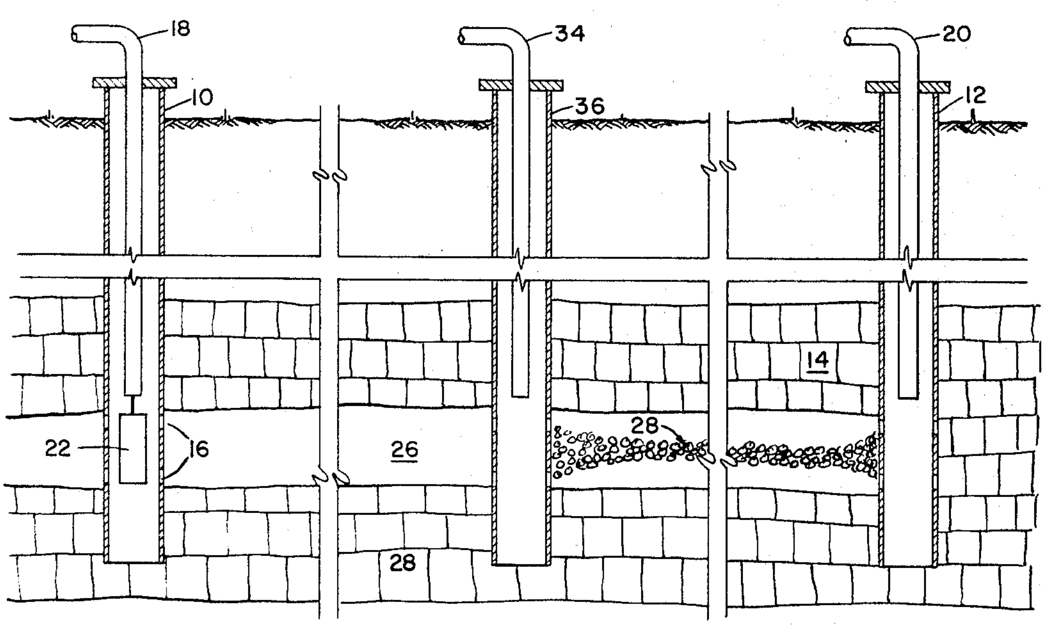

FIG. 4

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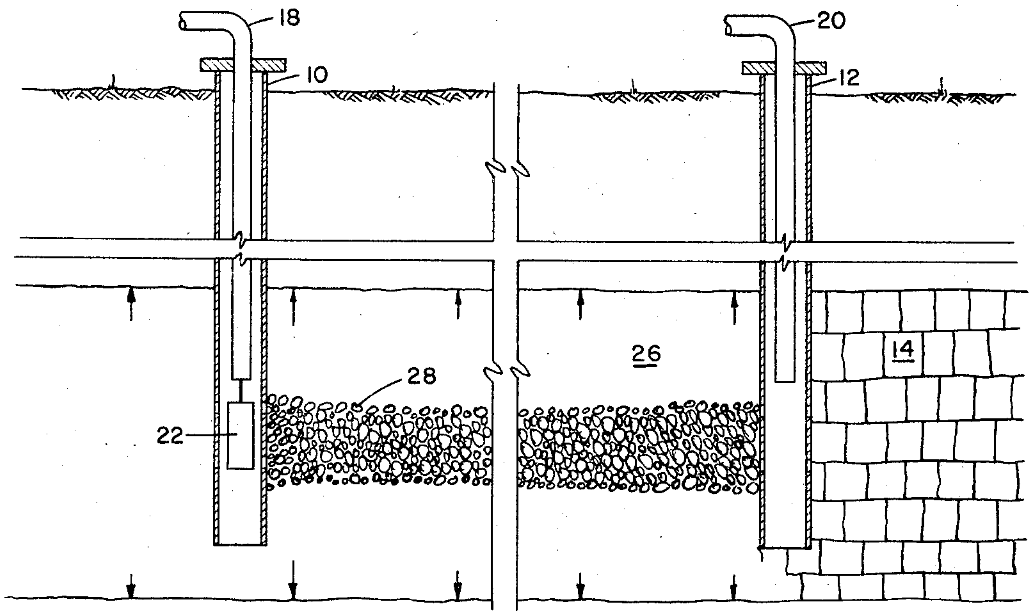

FIG. 5

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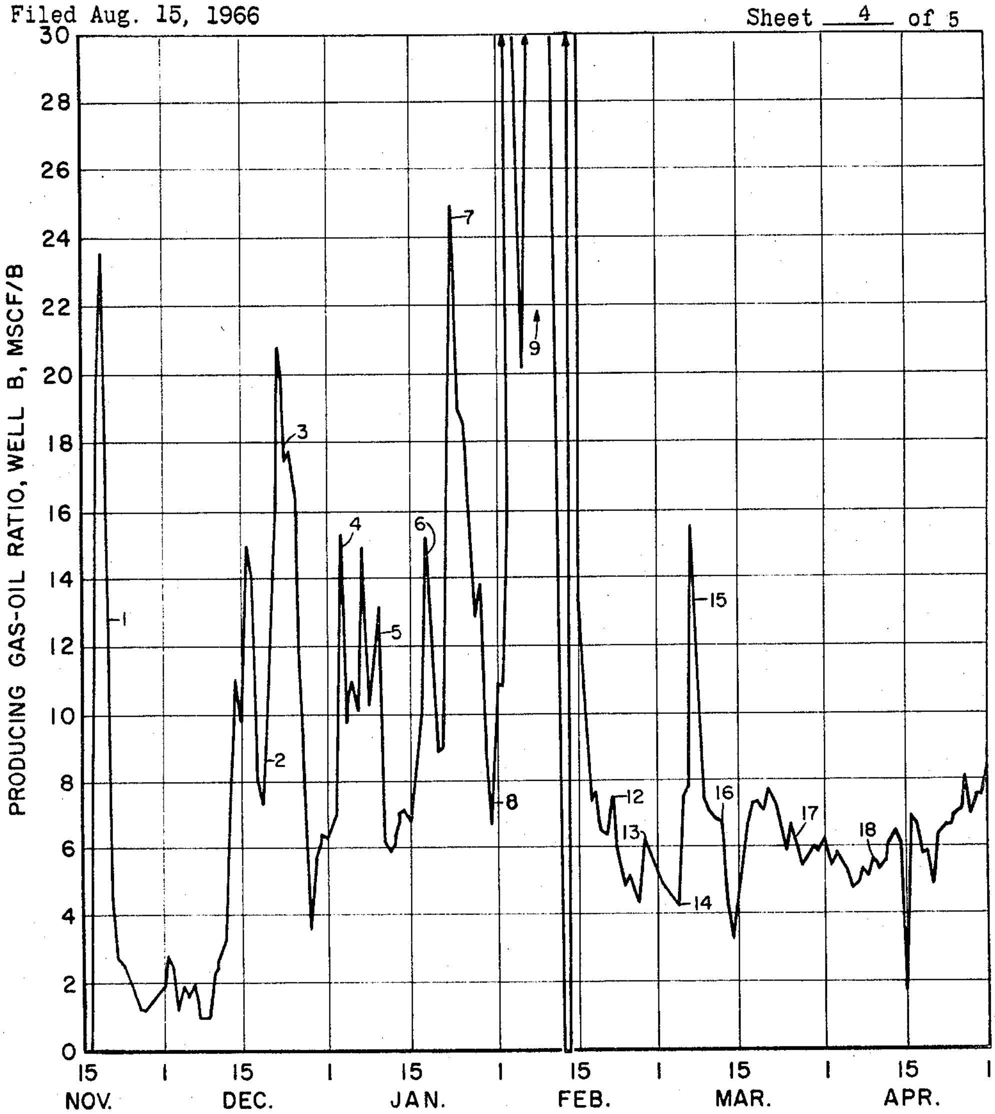

FIG. 6

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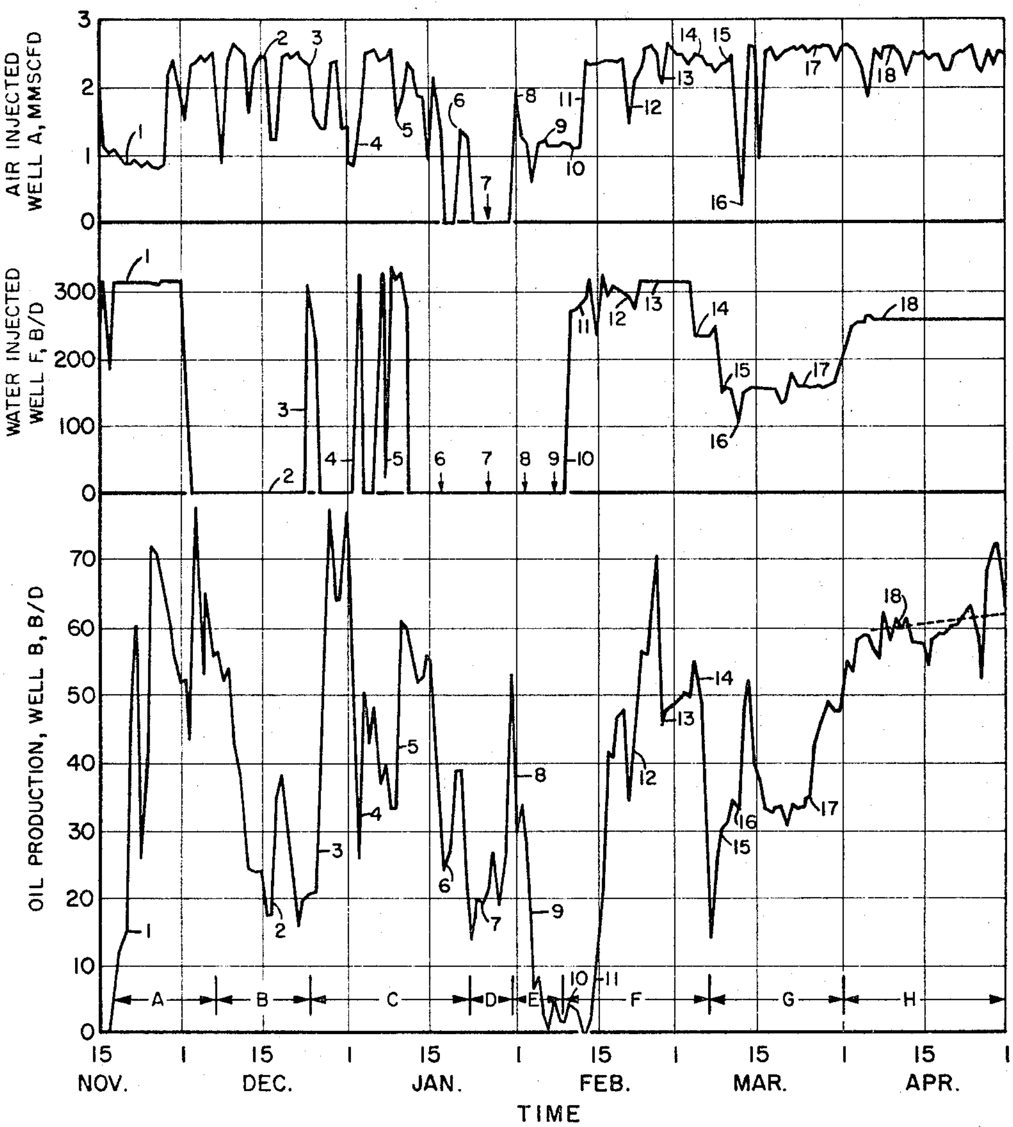

FIG. 7

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RAPID BREAKTHROUGH IN SITU COMBUSTION PROCESS

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Int. Cl. E21b *43/24*

ABSTRACT OF THE DISCLOSURE

A forward burning in situ combustion process wherein channeling is encouraged to produce a rapid breakthrough of the combustion front at the production well. Combustion of the bypassed hydrocarbon-containing portions of the formation is then carried out by injecting a noncombustible fluid such as water or an inert gas to plug the more permeable burned out portions of the formations while continuing the injection of a free oxygen-containing gas.

The present invention relates to an improved method for conducting subterranean combustion of carbonaceous materials. More particularly, this invention relates to an improved in situ combustion process for more complete recovery from a reservoir of crude oil, tar, oil shale or similar hydrocarbonaceous materials.

A popular method of recovery of hydrocarbonaceous materials from subterranean reservoirs is in situ combustion. In one form of the in situ combustion process, a free or molecular oxygen-containing gas, hereinafter referred to as an oxygen-containing gas or air, is injected into a hydrocarbon-containing formation at one well, called the injection well. Combustion of the hydrocarbon material is initiated at that well by suitable known means such as a downhole heater or injection of heated air. The injection of the oxygen-containing gas is continued to maintain combustion and force the oil in the formation to an adjacent well, called the production or recovery well, through which the oil and combustion products are lifted to the surface. This is the so-called forward burning or direct air drive technique. Another form of the in situ combustion process, referred to as the reverse air injection method, is similar to the previously-described process except that the oxygen-containing gas is injected into an injection well ahead of or countercurrent to the advancing combustion front rather than behind the combustion front. The combustion front is initiated at the production well and "backs" toward the source of air.

The aforementioned direct air drive technique has been found to have many advantages over the reverse air injection method. For example, the reservoir ahead of a combustion front moving in the reverse direction may contain tar, oil shale, a heavy viscous oil, liquid hydrocarbons, and connate water. Thus, the movement of an oxygen-containing gas through the reservoir ahead of a combustion front, as by reverse air injection, may be quite restricted and it is sometimes difficult to inject enough air to support combustion. In contrast, injection of an oxygen-containing gas behind a combustion front as by the direct air drive method is generally relatively easy. The problem then is downstream of the combustion front, three phase flow and cool producing wells, which can also restrict air injection.

At the same time, direct air injection techniques as previously practiced have several disadvantages. In reservoirs having varying permeability and containing high viscosity oil, it has been difficult to provide the proper amount of heat at the right time and in the proper place to achieve and maintain effective viscosity reduction. One

of the characteristics of in situ combustion in such reservoirs has been fingering or breakthrough of the injected gas and the combustion front at one or more production wells before the combustion front has swept the desired area. Such fingering has long been looked upon as undesirable, since it has generally been followed by a rapid rise in the injection rate of the oxygen-containing gas required for further oil production, a decrease in the oil production rate, an increase in the produced gas/oil ratio and a frequent uncontrollable increase in the bottom hole temperature due to the reaction of increased amounts of free oxygen and crude oil in the recovery wellbore. Many methods have been devised to prevent fingering and provide a means of advancing as uniform a combustion front as possible.

One method of maintaining a uniform combustion front, as well as controlling the temperature of the front, i.e., keeping the temperature from becoming too high as burning proceeds through the formation, is to inject water into the injection well either at the same time as air is injected or in alternate slugs therewith. The water contacts the hot burned out portion of the formation and at least partially vaporizes. The resulting steam or steam-hot water mixture passes through the combustion front and tends to cool off the same. As the steam contacts the relatively cool formation ahead of the combustion front, it condenses, thus preheating this portion of the formation and creating a pressure differential which aids in promoting further forward movement of the combustion front and displaced material. Thus, it has been postulated that the combustion front moves forward uniformly and sweeps the entire hydrocarbon-containing zone.

However, in many zones subjected to in situ combustion, especially those of considerable thickness, as more than 25 feet thick, it is questionable whether the combustion front can be uniformly moved through the zone in spite of the abovementioned techniques. It is also questionable whether the maximum amount of hydrocarbons can be recovered from such a zone by these techniques, e.g., avoiding fingering and maintaining the combustion front as uniform as possible and at as low a temperature as possible.

Accordingly, it is an object of this invention to efficiently and economically recover oil from a subterranean formation by in situ combustion. A further object is to improve still further the recovery of oil, especially heavy oil, tar, oil shale, and the like carbonaceous materials by in situ combustion. A still further object is to provide an in situ combustion process in which a rapid dissemination of heat throughout the reservoir is achieved. It is another object to provide an in situ combustion process which is especially applicable to relatively thick zones. An additional object is to provide an in situ combustion process which utilizes the heat produced in one layer or section of strata to partially produce an adjacent layer or section of the strata. Various other objects, advantages and features of the invention will become apparent from the following detailed description read in conjunction with the accompanying drawings which illustrate the invention.

The objects of this invention are attained by an improved process in which:

(a) In situ combustion in a reservoir containing carbonaceous substances is initiated by conventional means in the formation adjacent an input or injection well over an interval constituting a fraction of the vertical section of the formation,

(b) Fluid comprising an oxygen-containing gas is injected into the formation via an injection well at high pressures to propagate a combustion front through the formation for rapid breakthrough at an output or recovery well, and

(c) The character of the fluids injected into the formation is altered to achieve a reduction in the gas/oil ratio at the output well as well as heating and removal of carbonaceous materials from bypassed portions of the formation not appreciably affected by the combustion front during the step of rapid propagation of the combustion front to an output well.

A more complete understanding of the invention may be had by reference to the accompanying schematic drawings. FIGURES 1, 2, 3, 4 and 5 are vertical views in partial section showing a well arrangement for effecting the present invention. FIGURES 6 and 7, respectively, graphically show the produced gas/oil ratio with respect to time, and the volumes of fluids injected and produced relative to time. Referring to all the drawings, reference character **10** designates an injection or input well, and reference character **12** designates each of one or more recovery, production or output wells arranged in spaced relation around the injection well. The wells penetrate a carbonaceous substance-containing stratum **14**. Input well **10** is provided with perforations **16** extending over the central portion of stratum **14**. Input well **10** is also provided with conduit **18** for injecting fluids into the well and recovery well **12** is provided with conduit **20** for withdrawing fluids from the well.

Referring now particularly to FIGURE 1, electric heater **22** is positioned in input well **10** opposite perforations **16** and used to heat the surrounding stratum to combustion supporting temperature. While this temperature is being reached, an oxygen-containing gas is injected into the stratum opposite heater **22** via conduit **18** and through perforations **16**. Upon ignition, combustion front **24** forms and moves outwardly from input well **10**, as shown by the arrows.

FIGURE 2 illustrates the process just after rapid breakthrough of combustion front **24** has been achieved at recovery well **12**, showing that burning has taken place almost exclusively in the middle portion of stratum **14** extending between input well **10** and recovery well **12** with the remaining upper and lower portions of stratum **14** essentially unaffected.

FIGURE 3 shows the process during the stage in which the character of the fluid injected into injection well **10** has been altered to effect heating and removal of carbonaceous material from bypassed portions of the formation. Fluid flowthrough combusted zone **26** has been restricted by injection therein of slugs of a diverting fluid, such as water, which permeate zone **26**, as shown by reference character **28**, and divert the oxygen-containing gas or mixture thereof with inert gas and hence combustion front **24** into superjacent zone **30** and subjacent zone **32** of stratum **14**.

FIGURE 4 represents an alternate embodiment of the invention in which diverting fluid **28** is added through conduit **34** of secondary injection or intermediate well **36** disposed between injection well **10** and recovery well **12**.

FIGURE 5 illustrates the invention near the close of the process in which diverting fluid **28** plugs depleted zone **26**, the combustion front has traveled almost completely through originally bypassed superjacent zone **30** and subjacent zone **32**, and the carbonaceous material therein has been recovered through recovery well **12**.

In situ combustion may be initiated by any of several well known methods, as by locating an electric heater within the well at the level of the formation to be ignited with concurrent injection of air to start combustion in the region immediately surrounding the well. Alternatively, gas or liquid fuel may be burned in the air at the bottom of the well to produce a flame to ignite the immediate surrounding regions. After ignition of the formation has been accomplished, the heater may be removed or the initiating fuel discontinued.

A critical aspect of this invention is that the combustion front formed extends over only a fraction of the vertical cross sectional area of the oil stratum. Wide combustion fronts extending throughout the entire oil zone are difficult to control and require large amounts of air to sustain. The object of this invention is to form a narrow combustion front which requires less air to be quickly extended through a portion of the formation to achieve rapid breakthrough at the recovery well or wells. The vertical thickness of the combusted zone is sized so that the total heat liberated in this zone by passage of the combustion front therethrough is sufficient to heat bypassed portions sufficiently to provide substantial viscosity reduction or formation hydrocarbons. This limited combustion front can best be achieved by limiting the area of the stratum initially exposed to air injection. Thus, in one embodiment of this invention only a portion of the oil zone is perforated initially. These perforations can be located in either the upper or lower portion of the oil stratum. However, it is preferred that the middle portion, approximately the middle 25 to 50 percent of the oil zone, be perforated as later heat effects can extend both upwardly and downwardly to free additional oil. The combustion front propagated through the formation should be at least 10 feet thick, as this is the minimum cross section that can be maintained efficiently in most reservoirs even using high air injection rates. Where the oil-bearing formation is more than 20 feet thick, the initial combustion front can be from 10 feet thick up to half the thickness of the formation.

After combustion is initiated, the combustion front is rapidly propagated by forward burning at maximum velocity from the input well to the recovery well through a narrow section of the formation by feeding air thereto via the input well at a high injection rate. The combustion front can be propagated at maximum velocity by applying air pressure at the injection well approximately equal to the overburden pressure of the formation. Overburden pressure increases about 1 p.s.i. per foot of depth for most wells. If the producing formation is covered by a competent cap rock, the injection pressure of the gas may be raised to several hundred p.s.i. in excess of the overburden pressure, for example overburden pressure of 0.75 to 1.0 p.s.i./ft. plus up to 0.25 to 0.50 p.s.i./ft.

Breakthrough of the combustion front at the recovery well may be detected by a sudden increase in both the bottom hole temperature and the produced gas/oil ratio and/or gas rate. At this time the uncombusted portions of the formation lying above and below the combusted zone are exposed to heating along their interface with the combusted zone. This spreads the heating effect over a much wider area at a faster rate than if a combustion front is initially moved through the entire oil zone.

As soon as breakthrough occurs, steps are taken to produce hydrocarbons from these bypassed uncombusted portions of the formation. First, it is necessary to treat the formation in some manner to control the high gas/oil ratio at the recovery well. If this is not done, most of the air injected into the formation will simply follow the path of least resistance, i.e., flow through the previously combusted zone, and do only a minimum amount of work in aiding recovery of hydrocarbons from bypassed zones.

Thus, the fluid injected into the formation is altered to a fluid which will enter and at least partially plug or block the previously combusted zone of high relative permeability. This is done by reducing the air or gas injection rate and pressure and substituting for a portion of the free oxygen-containing gas a liquid fluid of higher viscosity than the gas, such as brine, water, emulsion, gel or other aqueous media. This aqueous fluid enters the zones of high permeability, thus diverting the low viscosity gas also being injected to the less permeable zones of the formation, i.e., those sections of the formation still containing combustible hydrocarbons. The amount of diverting fluid required is determined by measuring the gas/oil ratio at the recovery well. Whenever the gas/oil ratio gets above a desired level, e.g., above about 10,000 s.c.f./bbl., additional amounts of an aqueous medium is injected into the input well. The aqueous medium can be injected simultaneously with the gas. However, it is preferred to inject the two fluids alternately with gas being injected most of the time to move the combustion front through the uncombusted zones and a slug of aqueous medium being injected whenever the gas/oil ratio at the recovery well becomes excessive. In addition, recycle gas may be substituted for a portion of the injected gas to help lower temperatures at the recovery wellbore. This recycle gas may conveniently be that gas produced from the recovery well or other nearby wells in the pattern.

Generally, the aqueous media is injected via the original input well. Alternatively, an intermediate well lying between the input well and the recovery well may be utilized. The intermediate well may be drilled at the same time as the other wells in the pattern, or it may be drilled later when breakthrough at a recovery well has or is about to occur. This delay drilling of the intermediate well is often preferred in recovery from patterns where a combustion front is driven from a single input well toward a plurality of surrounding recovery wells. When breakthrough occurs at one of the recovery wells, which well's identity frequently cannot be determined in advance, an intermediate well can then be properly located and used to control the gas/oil ratio at this recovery well until the combustion front reaches a second recovery well. Other intermediate wells can similarly be properly located and utilized until the combustion front has broken through into all original recovery wells. This intermediate well may be utilized for injection into the formation of an aqueous diverting medium, a combustion-supporting gas, or both.

When the combusted zone has been partially blocked by the aqueous medium, additional injected gas is diverted to the less permeable zones still containing hydrocarbons. Thus, the entire interface between the narrow combusted zone and the uncombusted zones becomes a new combustion front which moves vertically through the uncombusted zones to liberate therefrom hydrocarbons which flow laterally toward a recovery well. Production of fluids may be enhanced by perforating the injection well, the recovery well or both throughout the entire vertical extent of the hydrocarbon-containing zone following initial breakthrough of the combustion front. The combined effects on the hydrocarbons remaining in the formation of this rapid dissemination of heat throughout the reservoir, i.e., heating by conduction from the narrow combusted zone, plus the extensive combustion zone along the interface between the narrow combusted zone and the uncombusted areas of the formation, result in volatilization or a rapid decrease in viscosity of these hydrocarbons and promotes their effective displacement to a recovery well.

EXAMPLE

The processes of this invention were illustrated by a series of treatments given a pattern of wells in the North Tisdale Field, Johnson County, Wyo. The area of interest involved a typical five-spot well pattern where the wells were on 10-acre spacing. The cased wells were 1050 feet in depth, perforated over the interval from 926 to 976 feet, and penetrated an oil-bearing formation which extended over the interval from 920 to 990 feet. The formation had an average permeability of 800 md. and produced an oil having a gravity of 21° API and a viscosity of 180 cps.

Well A, the central well of the pattern, was ignited over the interval 926 to 976 feet, and the resulting combustion front started rapidly moving through the formation by injecting about 800M c.f.d. of air and simultaneously producing corner wells of the pattern, B, C, D, and E. Fourteen months later, intermediate well F was drilled in the path of the advancing combustion front some 200 feet from well A on a line between wells A and B, and completed in a manner similar to that employed for the other wells of the pattern. Well F produced by flowing the

production up the tubing string into a test separator where rates were measured and controlled. After five days, a high bottom hole temperature of 350° F. was observed in well F, indicating the arrival of the combustion front. Production of well F and air injection into well A was continued. Some 16 months later the bottom hole temperature of well B went from 72° F. to 180° F. over a 12-hour period. This indicated that the combustion front had arrived at well B.

At this point, the process of this invention was carried out over the next 12 months by injecting gas in well A, injecting water in intermediate well F and producing well B. FIGURES 6 and 7 show graphically the volume of fluids injected and produced over this time period, as well as the gas/oil ratio at well B. By comparing the various numbered points placed on the graphs to aid in interpretation thereof, it can be seen that points **1**, **3**, **4**, **5**, **10**, **12**, **13**, and **16** show an increase in oil production rate resulting from simultaneously reduced air injection rates at well A and various water injection rates at well F. Points **2**, **6** and **7** illustrate trends toward increased oil production with conflicting GOR effects that resulted from air injection rate and pressure reductions at well A without any water injection at well F. Points **8** and **9** show that increased air injection rates without water injection results in decreased oil production and high GOR's. Points **10** and **11** show that water injection will not relieve a bad air channel immediately, but in the instance cited it required about 3 days of 1000 bbls. of water per day to effect a production increase. Points **14**, **15**, **16** and **17** show that reduced amounts of water can reduce the oil rates and increase GOR's. Points **16** and **18** show that reduced air rates or increased water rates can restore productivity at economical rates and low ratios.

To summarize, the intervals A, C, F, G and H illustrate the benefits of injecting water at an intermediate well while injecting air at on original injector. Intervals B and D suggest the benefit of reduced air rates and pressures without water injection, and the intervals B and E illustrate the unsatisfactory performance resulting from high-rate air injection without any water injection.

The foregoing description and illustration of the invention have related to certain specific processes whereby the objects of the invention are fully accomplished. It is readily apparent that many modifications can be made in the disclosed processes without departing from the spirit and scope of the invention as set forth in the appended claims.

We claim:

1. An improved in situ combustion process for a subterranean formation containing carbonaceous materials and penetrated by an input well and at least one recovery well comprising:

(a) establishing a combustion front by conventional means over a fraction of the vertical cross section of said formation adjacent said input well,

(b) injecting a fluid comprising a free oxygen-containing gas into said formation at a pressure at least equal to the overburden pressure to propagate said combustion front through said formation for rapid breakthrough at the recovery well,

(c) injecting into said formation a noncombustible fluid selected from the class consisting of water and an inert gas to decrease the gas/oil ratio at the recovery well and supply additional heat to the sections of said formation previously bypassed by the combustion front, and

(d) recovering carbonaceous materials from said bypassed sections at the recovery well.

2. The method of claim **1** wherein the free oxygen-containing gas is injected into the formation at a pressure of from the overburden pressure to a pressure of 0.25 to 0.50 p.s.i./ft. in excess of the overburden pressure.

3. The method of claim 1 wherein the noncombustible fluid selected from the class consisting of water and an inert gas and free oxygen-containing gas are injected as alternate slugs of fluid.

4. The method of claim 1 wherein the inert gas is recycle gas.

5. The method of claim 1 wherein the non-combustible fluid is injected into the formation via an intermetiate well positioned between the injection well and recovery well.

6. The method of claim 1 wherein the combustion front established has a minimum thickness of 10 feet and a maximum thickness of half the total thickness of the formation being combusted.

7. The method of claim 1 wherein the free oxygen-containing gas is injected into the formation at a pressure of at least 1 p.s.i. per foot of depth.

8. The method of claim 1 wherein the free oxygen-containing gas is injected into the formation at a pressure of from 1 to 1.5 p.s.i. per foot of depth.

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