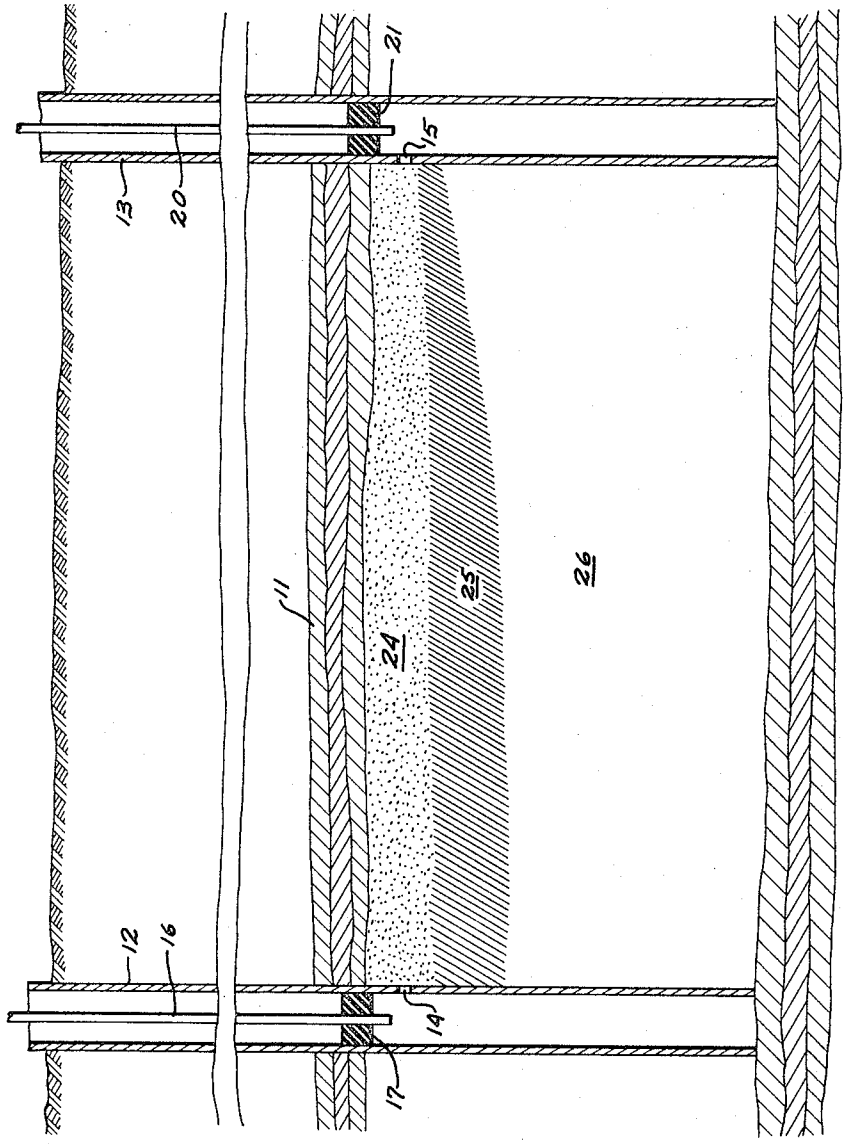
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IN SITU COMBUSTION PROCESS

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IN SITU COMBUSTION PROCESS

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ABSTRACT OF THE DISCLOSURE

A method of injecting oxidizing gas into the upper boundary of an oil-bearing formation, initiating in situ combustion and forming a channel of increased permeability adjacent to the upper boundary of the oil-bearing formation between an input well and an output well, decreasing air injection into the input well to maintain the produced gases' oxygen content below five percent on a hydrogen-free basis and producing, from the upper boundary of the oil-bearing formation to the surface, upgraded oil and fluids which enter the output well.

This invention relates to the upgrading of crude oil in an underground reservoir and to the production of the upgraded product. The invention particularly relates to an in situ combustion process which is carried out for the maximum recovery of upgraded product.

Conventional or primary recovery techniques for recovering and producing oil in general produce between ten and thirty percent of the oil originally occurring in the underground reservoir. Many supplemental or secondary recovery techniques have been suggested such as waterflooding, gas drive, thermal recovery, etc., and various of these have been used where they have been operationally and economically justified. The thermal methods of recovery include the injection of heated liquids of gases into the oil bearing formation and in situ combustion.

The conventional forward drive in situ combustion process is employed as a recovery technique for the production of crude oil in situations where the reservoir characteristics, and crude oil properties economically justify this recovery approach. Air is injected into an input well and combustion is initiated by one of many accepted methods. It is hoped as an optimum result that the zone of combustion will move as a radial front from the input well and drive the reservoir oil ahead of it to the production well. However, the combustion gases and oil may become segregated with the gases riding over the oil and channeling through the top of the formation as a result of the difference in densities and the increased flowability of the heated oil. This overriding flame front prematurely breaks through into the production well prior to a substantial production of the oil. Once this breakthrough has occurred the continuation of air input will result in an increasing amount of unreacted oxygen being produced in the output wells with a decrease in oil production. The occurrence of appreciable quantities of free oxygen in the output well in the presence of hydrocarbon materials at elevated temperatures poses a very real fire hazard. In addition, the reduction in oil production as well as oxygen usage renders the process economically unsuitable after segregation and breakthrough has occurred.

Efforts have been directed towards solving the problems introduced by this tendency of the reservoir to become stratified by the oxidizing gas overriding the oil. In one instance it has been suggested that a combustible hydrocarbon be injected into the top of the formation adjacent the input well to insure complete reaction of all of the oxygen in the combustion-supporting gas. While the reservoir oil which is burned in in situ combustion does not represent an out-of-pocket expense to the operator, the fuel injected by this process represents a significant expense which may well render the recovery economically unfeasible. Another proposal suggests the separate recovery of the segregated crude oil and the overriding gas during combustion in order to keep hot oxidizing gas away from the oil product, but this involves a concomitant low oxygen utilization.

Some crude oils as they occur in the reservoir are of such low quality and high viscosity that they are produced only with difficulty at a substantially increased expense over light crudes. And once they are brought to the surface they must be prerefined at a cost amounting to as much as fifty percent of the wellhead price of the oil in order to put them in condition for conventional refining. It would be economically desirable if such an oil could be pretreated in the reservoir and produced as a prerefined upgraded oil.

I have discovered that in situ combusion can be carried out within the reservoir in a manner which will result in the recovery of a substantially upgraded product in the output well. In my process the inherent tendency of the combustion gases and oil to segregate with the combusion gases overriding the oil bank, which hitherto has been considered to be a serious impediment to the successful execution of conventional forward combustion, is advantageously utilized for the modification and production of the reservoir oil into an upgraded form. Perforation of the input well and the production well above the oil bank is an essential feature of my invention. A burned out, override zone or zone of high permeability above the reservoir oil is produced and is utilized in conjunction with in situ combustion of reservoir oil under specific conditions of operation for the upgrading process. The upgraded product results from the thermal distillation of the lower boiling fractions together with the thermal cracking of the high boiling fractions and asphaltic materials in the presence of an oxidizing gas. The resulting combustion gases sweep through the zone of increased permeability to the production well carrying the upgraded fluids with them with a minimum encroachment of reservoir oil into the production well. Thus, I have discovered that the tendency of the combustion gases to override the reservoir oil can be utilized by appropriate adjustment of operating procedures and conditions to produce an upgraded product. Although any combustion-supporting gas which is usable in in situ combustion such as oxygen, oxygen enriched air, and air is usable in carrying out my process, I prefer to use air due to inherent economy and my invention will be discussed with air as the oxidizing gas.

Since my invention involves the use of a path of high permeability above the oil bank, it is desirable initially to produce this path of high permeability as quickly as possible in order to operate under conditions for maximum upgrading. The input and output casings are perforated at the upper part of the pay zone and air is forced into the formation under high pressure, and forward combustion initiated using conventional procedures. Forward combustion is maintained at a high rate until thermal breakthrough has occurred as determined by monitoring the temperature of the output well or by analysis for oxygen in the output gas. The oil produced prior to breakthrough is essentially unmodified reservoir oil. Alternatively a highly permeable zone may be produced from the input well to the output well along the upper perimeter of the oil zone by fracturing techniques and/or by the injection of a low viscosity solvent in accordance with accepted procedures. A further modification involves the use of an existing depleted gas cap barren of residual oil as a path of high permeability. This may be utilized by injecting a supplemental fuel such as LPG to support the initiation of combustion. Once this path of high permeability has been established in the upper portion of the

pay zone between the input and output perforations, the injection of air and rate of combustion is maintained at a level which will result in a predetermined, low level of oxygen in the output well without thermal breakthrough. I have discovered that under these conditions combustion unexpectedly is maintained in the formation with the production of an upgraded material consisting in large part of distillate material.

Prior to my discovery it was believed that combustion below a burned out zone could only result from the diffusion of air down to the oil zone with a concomitant low utilization of oxygen. Mathematical analysis based upon diffusion rates indicates that efficient combustion will not be supported under this theory alone. However, my discovery that combustion with efficient oxygen utilization can be conducted under certain, specific conditions indicates that more than gaseous diffusion is involved. It is my belief that convection currents are involved as well as gaseous diffusion to bring the air and oil into reactive contact.

My invention may be utilized for the secondary recovery and upgrading of oil in wells which have exhausted their natural reservoir drive or which originally lacked sufficient natural drive and which are amenable to in situ combustion techniques. Upgrading is a relative term which is used to indicate an increase in both quality and value. The upgraded oil recovered from the reservoir will contain a greater proportion of the more valuable lower boiling materials and a smaller amount of the less desired high boiling materials than the virgin oil with substantial elimination of heavy asphaltic fractions and inorganic catalyst poisons including nitrogen, sulfur and heavy metals such as nickel, vanadium and iron, and it may wholly comprise distillate products. Since the recovery of lower boiling liquid fractions is the general objective, the relative increase in API gravity serves as a rough indication of the degree of upgrading.

In producing an upgraded product by this process it is desirable to obtain a sample of reservoir crude and subject it to distillation and thermal cracking in the laboratory in simulation of underground conditions under my process. The product is representative of the product to be obtained from the production well by optimum operation of my invention and may be used as a standard in evaluating the operation of my combined in situ combustion-upgrading process.

The invention will now be more specifically described in connection with the drawing which illustrates the production of an upgraded product from an oil bearing formation. This formation is located immediately below an impervious rock formation **11**. Casing **12** of the input well and casing **13** of the production well project from above ground to the bottom of the oil formation. Each casing is perforated **14** and **15**, respectively, at the upper portion of the oil formation. Air is injected into the input well through tubing **16** positioned in packer **17** and enters the oil formation through perforation **14**. The combustion gases and upgraded product enter the production well through perforation **15** and are produced through tubing **20** set in packer **21**.

The drawing illustrates the operation conducted under conditions for maximum upgrading. Prior to this, the highly permeable, burned out zone **24** was formed by injecting air into the formation under high pressure with initiation and continuation of combustion until thermal breakthrough occurred at perforation **15**. Prior to breakthrough at the production well, conventional forward combustion took place in zone **24** with the combustion front sweeping reservoir crude ahead of it into the production well. Thermal breakthrough was determined by monitoring the temperature of the output well. When the temperature rose to about 300° to 400° F., thermal breakthrough was imminent. The upgrading phase was then initiated by reducing the air pressure to a lower value to maintain combustion at a rate sufficient to keep the oxygen content of the combustion gases in the output well below about five percent on a hydrocarbon-free basis. In addition, the temperature in the production well is maintained at a value less than about 300° to 400° F. or less than that temperature at which combustion would be supported.

A high temperature front between about 600° to 1600° F. and more probably between about 800° to 1200° F. exists in the burned out zone **24** as a result of the earlier combustion to breakthrough. This high temperature zone provides a barrier effect to the upward movement of heat from combustion zone **25** ensuring that a large fraction of the heat generated in the combustion zone will be directed downwardly. As the air injected into the preburned zone **24** progresses through the formation it is heated in the preburned zone and moves downwardly to the combustion zone by a combination of convection and diffusion currents. The downwardly moving heat front directly volatilizes the lighter hydrocarbon components while the heavier components are cracked producing more volatiles and depositing a coke on the grains in the combustion zone. The downwardly moving oxidizing gas burns this coke in the combustion zone fortifying the downwardly moving heat front. The combustion gases and vaporized hydrocarbons move upwardly by convection currents and by diffusion.

The gross movement of the commingled combustion gases and hydrocarbon vapors in the hot burned out zone is in the direction of the output well with localized vertical components of motion resulting from the diffusion and convection currents. As these gases and vapors move towards the output well, a gradual cooling occurs in the vicinity of the output well. Some of these hydrocarbon vapors will be carried out into the production well with the combustion gases while the higher boiling portion will tend to condense and be forced into the production well by the pressure of the combustion gas and vapors. Since the production well perforation **15** is located above the level of the reservoir oil **26**, this oil is restrained from flowing into the output well by gravity. If necessary, an anti-coning barrier may be placed immediately below the output perforation as a further restraint against the production of reservoir crude. This upgrading operation may be evaluated at any stage of operation by comparing the specific gravity of the upgraded product recovered from the production well with the specific gravity of the sample previously thermally treated in the laboratory in simulation of the underground conditions.

Injection of air and upgrading combustion is continued for the total recovery of reservoir oil. The pressure of the injected air is varied to control the oxygen content of the combustion gases on a hydrocarbon-free basis to less than five percent and preferably as close to one percent or below as possible. If the oxygen content increases above the desired level, the air flux is decreased; however, the air flux should be maintained at a rate to cause significant production of the desired product. When the oxygen content rises above five percent and cannot be lowered without reducing the air flux to an economically unattractive level, it is an indication that the reservoir oil has been cleaned out to a level substantially below the perforations. One of several techniques may be used to prevent or remedy this situation. Water may be injected at a controlled rate into the base of the oil formation at the injection well as a vertical flood by imbibition to cause a general rise of the oil bank and feed oil to the combustion zones. Or, connate water, if present will progressively be expanded into steam by the downwardly moving heat front and will induce the oil bank to rise to the desired level. Also, steam may be injected directly into the base of the formation to carry oil upwardly. A further technique involves the progressive lowering of the perforations to a position no lower than the level of reservoir oil then existing and the upgrading combustion repeated as before to sweep away reservoir oil layer by layer by

distillation and thermal cracking. This latter approach is particularly useful with the less mobile oils. The upward movement of oil by capillarity and by expansion and vaporization of the oil by the downwardly directed heat front further aids in maintaining combustion. By proper selection of conditions and process controls, the reservoir can be cleaned out to produce the substantially more valuable upgraded product.

Since this process involves the injection of air at a moderate rate, it inherently involves production at a moderate rate. However, economic compensation is obtained not only in the substantial increase in the value of the upgraded product but also in the low air compressor costs involved in this process. By introducing air into a highly permeable formation, for example a burned out zone, at moderate rates relatively low air injection pressures are involved resulting in relatively low compressor costs per barrel of upgraded product.

This process was tested with a crude oil having an API gravity of 9.1° and a viscosity of 5,000 centistokes at 130° F. A nine and one-half foot combustion tube having an inner diameter of six inches was packed with 4–8 mesh sand to give a porosity of 45 percent. Capillary action was not a factor with this sand grain size. The crude oil was introduced into the pack to give an oil saturation of 58.2 percent and water saturation of 9.1 percent. The oil was presegregated by heating the tube in a horizontal position at 200° F. Air was injected at a constant rate of 40 s.c.f./hr./ft.^{2} and combustion was initiated. Upgrading was verified by condensing and collecting the product and analyzing it. After 102 hours of operation 73 percent of the crude oil was recovered as an upgraded product having an API gravity of 18.1° and a viscosity of 26 centistokes at 130° F. The sulfur content was reduced from 4 percent to 3.2 percent and the nitrogen content was reduced from 5910 p.p.m. to 983 p.p.m.

The process was further tested using the above cited oil in a rectangular model 8 feet long, 4 feet high and 1 foot thick. The model was packed with 10–20 mesh Ottawa sand to give a porosity of 38 percent. A region of high gas saturation was established in the top one and one-half feet by draining oil from the tank in this zone. Below this area the oil saturation was 100 percent. Combustion was initiated by hot air injection. A combustion zone was caused to move through the length of the model near the top and sweeping a vertical section one foot thick. Thirty-five percent of the initial oil was produced as an upgraded product having an API gravity of 12.5 and a viscosity of 860 centistokes at 130° F. The sulfur content was reduced from 4 to 3.13 percent and the nitrogen content was reduced from 5910 p.p.m. to 1691 p.p.m. Subsequent to this, ignition was again effected near the inlet and a combustion zone was caused to move through the length of the model at a level corresponding to the lower edge of the preceding traverse. An additional 9.0 percent of the initial oil was produced as an upgraded product exhibiting an API gravity of 16.4°.

I have discovered that superior results are obtained under high pressure operation. When operated at a pressure of 1000 p.s.i. a greater increase in API gravity elevation and greater elimination of inorganic components resulted as compared with operation at a lower pressure. Furthermore, the water from the high pressure operation showed a minimum pH of 6 as compared with a pH of about 1.5 to 2 when operated at a low pressure. This indicates that pressure operation suppresses the formation of low molecular weight oxygenated, water-soluble molecules. Comparative tests using hot nitrogen gas accomplished only a minimum upgrading indicating that the upgrading process requires the presence of oxygen as well as elevated temperatures.

The process is now described in the recovery of an upgraded product from an oil reservoir. The natural drive of the reservoir has been exhausted and the remaining oil content is about 1650 bbl./acre feet. The oil has an API gravity of 10° and a viscosity of 5000 centistokes at the reservoir temperature of 90° F. The crude oil is upgraded in the laboratory by simulation of underground conditions to a product having an API gravity of 16° worth approximately $0.30 U.S. more per barrel at the wellhead than the virgin crude. As a result of this analysis it is decided that my process is economically advantageous for the recovery of additional product.

The producing formation is 50 feet thick with a gradual slope. The injection well is located downstructure, which is the preferred alternative in sloping formations, and is perforated over a five foot interval at a depth of 1000 feet, adjacent to the top of the pay sand. The production well is located upstructure, 300 feet from the injection well, and is perforated adjacent the top of the pay sand over a five foot interval at a depth of 990 feet. Ignition is accomplished by preheating the injected air to 1000° F. using a suitable heating device. Air is injected into the input well at a rate of 2 million s.c.f. per day for seventy days until the temperature at the production well increases rapidly indicating imminent breakthrough of the combustion zone. Up to this time, the oil production from the output well is essentially virgin crude. When the temperature reaches 400° F., the air injection rate is decreased as required to maintain the oxygen concentration in the produced gas at less than five percent. During the first ten days of the second phase of operation while the air rate is adjusted, the air heater in the injection well is operated to preheat the air to 1000° F. In this second phase of operation a liquid product is produced from the well and the volatiles are condensed from the gases above ground. The combined product has an API gravity of 15.8° which represents substantially complete upgrading when compared with that obtained from the laboratory analysis. The upgrading is determined to be successful and is continued for maximum recovery of the oil.

This invention was described in connection with one input and one output well. However, it is intended and anticipated that it will be used in a variety of well patterns including conventional three-spot, four-spot, five-spot and line drive patterns. When one injection well is used in conjunction with several production wells, the rate of air flux towards each production well is controlled at the production well by pressuring each production well to an amount which will maintain the oxygen content in each well within the level specified herein.

This process is particularly suited to the recovery of poor quality crudes such as those having a low API gravity and requiring pretreatment or prerefining in order to be utilized in a conventional refinery. Not only is the product materially upgraded as measured by API gravity but it is also greatly improved by a significant reduction in the content of undesired inorganic constituents. The process may be used with any reservoir crude which is amenable to in situ combustion and which passes an economic analysis. Because of the substantial increase in the wellhead price of the upgraded product the recovery of uneconomic and marginal crudes may now be economically justified.

I claim:

1. A method of producing an upgraded oil from an underground oil-bearing formation by in situ combustion between an input well and an output well, each well having casing installed and cemented through the oil-bearing formation, comprising:

perforating the input well and the output well adjacent only the upper boundary of the oil-bearing formation;

forming a channel of increased permeability between the input well and the output well adjacent only the upper boundary of the oil-bearing formation;

thereafter injecting an oxidizing gas into the channel of increased permeability at a rate adjusted to maintain a zone of combustion adjacent the upper bound-

ary of the oil and to maintain the oxygen content of the combustion gas, delivered into the output well, below about five percent determined at the output well on a hydrocarbon-free basis; and

producing, from the output well to the surface, a substantially upgraded product.

2. A method in accordance with claim 1 in which the oxidizing gas is air.

3. A method as set forth in claim 1 wherein the channel of increased permeability is formed by injecting oxidizing gas at a relatively high rate downwardly through the input well and into the upper boundary of the oil-bearing formation and igniting the oil in the formation to burn through the upper portion of the formation until the temperature in the output well approaches about 300° to 400° F.

4. A method, as set forth in claim 1, wherein the channel of increased permeability is formed by hydraulic fracturing methods.

5. A method, as set forth in claim 1, wherein the channel of increased permeability is formed by injecting a solvent, having a viscosity lower than the in-place oil, down the input well and through the oil-bearing formation to the output well, to displace oil from the upper portion of the oil-bearing formation.

6. A method in accordance with claim 5 in which the oxidizing gas is air.

7. A method of producing an upgraded oil from an underground oil-bearing formation penetrated by an input well and a remotely located output well, each well having casing installed and cemented through the oil-bearing formation, a perforation formed through the casing of each well adjacent only the upper boundary of the oil-bearing formation and a channel of increased permeability formed through the upper boundary of the oil-bearing formation from the perforation of the input well to the perforation of the output well, comprising:

injecting oxidizing gas into the channel of increased permeability and igniting the oil-bearing formation to form a zone of combustion adjacent the upper boundary of the oil;

adjusting the rate of oxidizing gas injection to maintain the oxygen content of the combustion gases, delivered into the output well, below about five percent determined at the output well on a hydrocarbon-free basis;

maintaining the upper level of oil substantially adjacent the channel of increased permeability as combustion consumes the oil; and

recovering a substantially upgraded product from the output well.

8. A method as set forth in claim 7 wherein the oxidizing gas is air.

9. A method in accordance with claim 7 in which the upper level of the oil is maintained substantially adjacent to the zone of increased permeability by injecting water at the base of the input well to raise the oil bank.

10. A method in accordance with claim 7 in which the upper level of the oil is maintained substantially adjacent to the zone of increased permeability by lowering the input and output perforations as the upper level of the oil descends from combustion of the oil.

References Cited

UNITED STATES PATENTS

3,004,595	10/1961	Crawford et al.	166—11
3,087,541	4/1963	Elzinga	166—11
3,138,202	6/1964	Ewing et al.	166—11

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