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3,110,345

LOW TEMPERATURE REVERSE COMBUSTION PROCESS

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3 Sheets-Sheet 1

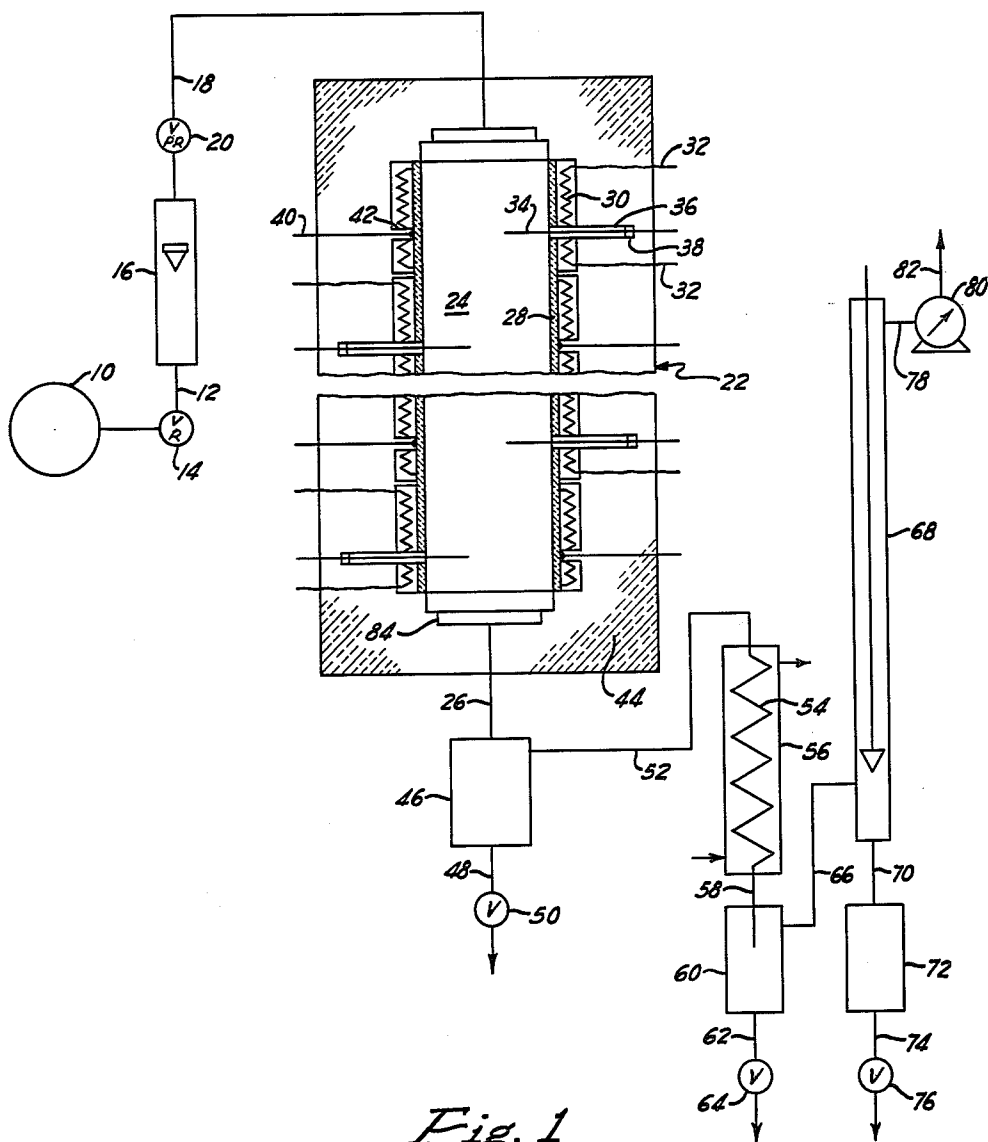


Fig. 1

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3 Sheets-Sheet 2

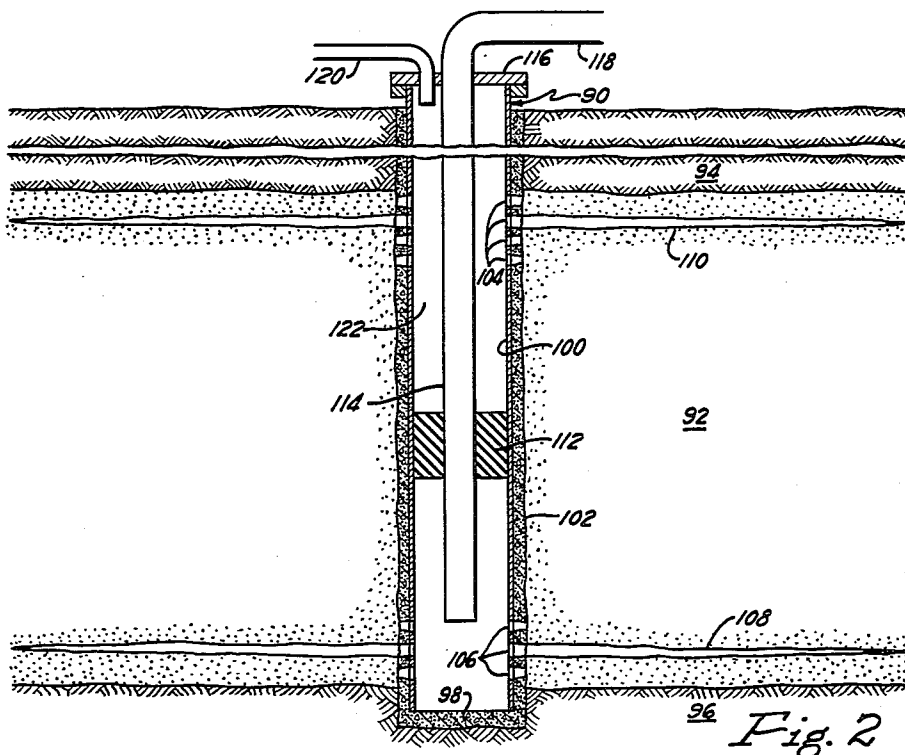


Fig. 2

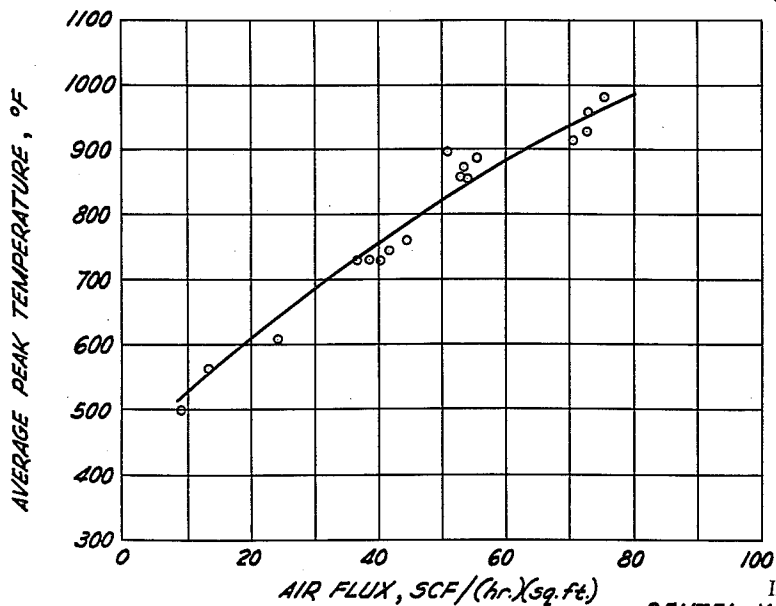


Fig. 3

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3 Sheets-Sheet 3

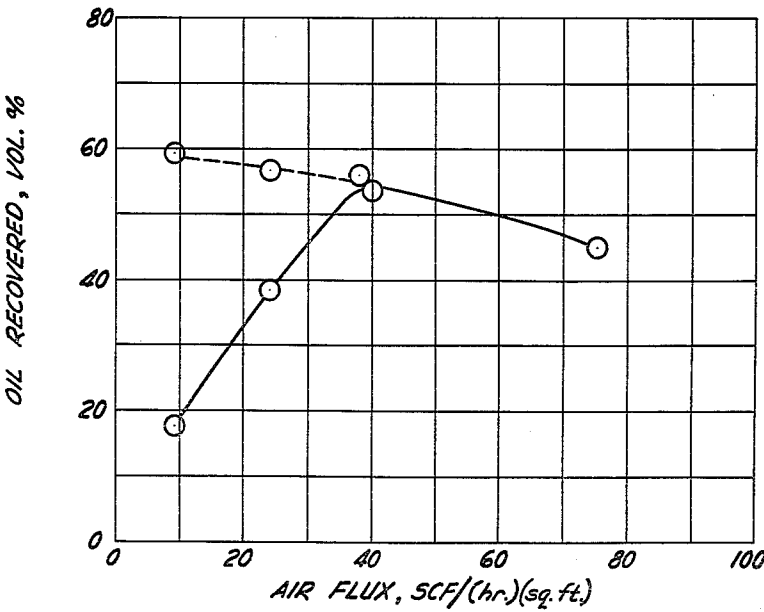


Fig. 4

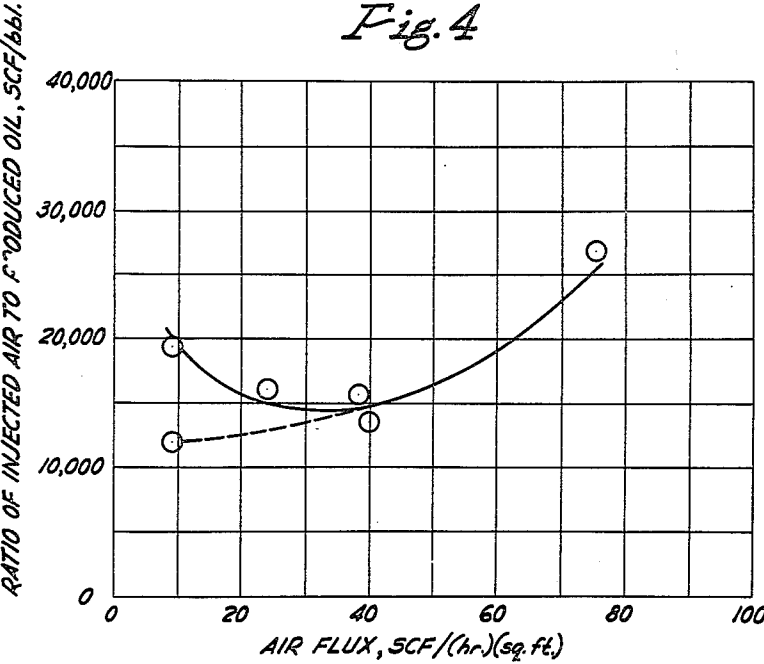


Fig. 5

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## LOW TEMPERATURE REVERSE COMBUSTION PROCESS

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Filed Feb. 26, 1959, Ser. No. 795,636  
1 Claim. (Cl. 166—11)

This invention relates to the production of oil by in-situ combustion in an oil-bearing formation and more particularly to an improved reverse combustion process.

In the conventional in-situ combustion process, an oxygen-containing gas is injected into the oil-bearing formation at one well, called the injection well, and oil in the formation is ignited at that well. The injection of the oxygen-containing gas is continued to force oil in the formation to an adjacent well, called the production well, through which the oil is lifted to the surface. In that process, which is ordinarily called a forward burning process, the movement of the combustion front and the flow of the oxygen-containing gas and products of combustion are toward the production well.

The forward burning in-situ combustion process has several very desirable characteristics. Once the combustion has started, the products of combustion traveling ahead of the combustion front distill lighter fractions from the oil and leave only the very heavy ends in the form of coke to be burned as the combustion front moves outward from the injection well. The portion of the formation behind the combustion front is clean and completely stripped of hydrocarbons. Thus, the forward burning process results in a minimum consumption of the oil in the formation.

Several factors often encountered in formations in which production by in-situ combustion may be desirable prevent the effective use of a forward burning process. The oil ahead of the combustion front may be a heavy, highly viscous oil. During the major part of the forward burning process, the oil and formation ahead of the combustion front are relatively cold. Hence, the viscosity of the oil remains high. Ahead of the combustion front is a multi-phase mixture which may include liquid and gaseous hydrocarbons, gaseous products of combustion, and condensed water. The water may be connate water originally present in the formation, water resulting from condensation of combustion products, or both. The presence of the several fluid phases in the formation greatly reduces the permeability of the formation to any one phase. As a result of these factors, often the resistance to flow is so high it is not possible to inject an oxygen-containing gas into a formation at rates high enough to allow economic production by a forward burning process or, in some instances, to maintain combustion.

An in-situ combustion method that has been developed for the production of heavy oils from formations such as tar sands is the reverse combustion process. In that process, an oxygen-containing gas is injected into the formation at the injection well and oil in the formation is ignited at an adjacent production well. The combustion front then moves from the production well towards the injection well. The oil produced by the process and the combustion products move in a direction opposite that of the combustion front and are discharged from the formation into the production well. In the reverse com-

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bustion process, the oil that is moved through the formation is hot and moves through a hot formation of increased permeability. Because of the lower viscosity of the hot oil and the increased permeability of the formation, the resistance to flow is much less than in the forward burning process. The conventional in-situ reverse combustion process is described in United States Letters Patent No. 2,793,696 of R. A. Morse.

The conventional reverse combustion process has an important disadvantage in that only a portion of the oil in the formation is burned or produced. The remainder of the oil is coked in place in the formation and is left in the formation as the combustion front moves towards the injection well. The coke represents oil that cannot be recovered from the formation. The injection of additional air into the formation after the combustion front has moved to the injection well merely burns the coke in place and produces carbon monoxide, carbon dioxide, and water. In spite of this disadvantage of the reverse combustion process, in many oil-bearing formations of low permeability or containing heavy oils, or in some partially depleted formations, it is the only effective method of recovering oil from the pay zone.

This invention resides in a low temperature reverse combustion process in which oil in a fluid form remains in the pay zone after the combustion front has passed and that oil may then be recovered from the hot formation by an appropriate subsequent secondary recovery step. Reverse combustion of the low temperature type is maintained and the peak temperature is controlled within narrow limits by regulation of the flux of the oxygen-containing gas injected into the formation. The term "flux" refers to the rate of injection of the gas in terms of volume of gas injected per unit area of the combustion front per unit of time.

FIGURE 1 is a diagrammatic illustration of experimental apparatus set up to observe the in-situ combustion process of this invention.

FIGURE 2 is a diagrammatic sectional view of a well adapted to perform a low temperature reverse combustion process according to one embodiment of this invention.

FIGURE 3 is a graph in which the peak temperatures attained by tar sands during experimental runs are plotted against the air flux.

FIGURE 4 is a graph in which the percent of oil in the tar sand that was recovered by several experimental runs of in-situ combustion processes is plotted against the air flux.

FIGURE 5 is a graph in which the standard cubic feet of air injected to recover a barrel of oil is plotted against air flux for several experimental runs.

The important advantage in the process of this invention resides in leaving a liquid residue in the oil-bearing formation after the reverse combustion step has been completed. The liquid residue being hot and in a hot formation can then be recovered by additional steps, for example, a forward combustion step, a gas repressuring operation, a water flood operation, or a fracture-gravity drainage step. The combination of low temperature reverse combustion with one of these additional recovery steps frequently gives rise to an improved process, with an improved oil recovery and improved over-all economics. In particular, the combination of low temperature reverse combustion with forward combustion as a

subsequent recovery step results in a process with a lower over-all air-oil ratio and hence better economics than could be obtained using conventional reverse combustion alone.

Whether or not the residue in the formation following the reverse combustion step is liquid depends upon the amount and extent of coking of the oil left in the formation. The extent of coking in turn will depend on the temperature reached by the formation as the combustion front passes through it and the nature of the oil left in the formation.

It has been found that the peak temperature attained in the formation depends on the flux of the oxygen-containing gas. Experimental reverse combustion runs were made on tar sands from six different sources. Several different oil saturations for the same tar sand were also used in different runs. In addition, runs were made when the tar sands had a relatively high water saturation in addition to the oil. The experimental runs were made in test equipment using five different types of combustion chambers which included transite pipe  $\frac{1}{4}$  inch thick with no external heaters, an insulated stainless steel pipe 5 inches in diameter with no external heater, and three different stainless steel pipes  $2\frac{1}{2}$  inches in diameter with heating elements and controls of different designs for temperature regulation. In spite of the wide variations in the nature of the tar sands and the experimental apparatus, it has been found that the peak temperature attained by the tar sands can be controlled within narrow limits by control of the air flux alone.

Experimental runs showing the dependence of the peak temperature, oil recovery, and air to oil ratio attained in reverse combustion processes upon the air flux were performed in apparatus diagrammatically illustrated in FIGURE 1 of the drawings. Referring to that figure, a compressed air container 10 is provided with a discharge line 12 in which there is a reducing valve 14 to control the pressure. A metering device 16, illustrated as a rotameter, in line 12 allows continuous measurement for control of the rate of flow of the air. A line 18 connects the discharge end of the rotameter 16 with the inlet of a combustion tube indicated generally by reference numeral 22 through a pressure reducing valve 20.

Combustion tube 22 illustrated in FIGURE 1 consists of a central tube 24 closed at its upper end except for connection with line 18 and at its lower end except for connection with a discharge line 26. Tube 24 is surrounded with a thin layer of insulation 28 around which are assembled electrical heaters 30 supplied with electrical power leads 32.

A thermocouple 34 is positioned in the center of the combustion tube 24 by passing it through a thermocouple well 36 and a gas tight seal 38 located on the end of the thermocouple well 36. A thermocouple 40 is located with its junction on insulation 28 by passing it through a hole 42 in heater 30. An outer layer of insulation 44 encloses the complete combustion tube assembly 22.

Thermocouples 34 and 40 and power leads 32 are connected to a control system (not shown in FIGURE 1) in such a way that whenever thermocouple 34 is hotter than thermocouple 40 electrical current is supplied to heater 30, and whenever thermocouple 40 is hotter than thermocouple 34 electrical current is not supplied to heater 30. Furthermore, the controller is so designed that the rate of heat generated by the heater 30 is in proportion to the rate at which the temperature at the center of the tube is increasing. Controllers of this kind are well known to those versed in the art. For the purpose of maintaining the entire combustion tube 22 in a locally adiabatic condition, a series of individual heaters 30, each with its associated thermocouple pairs (34 and 40), power leads 32, and proportional controllers, are provided along the length of the tube.

Discharge line 26 opens into the upper end of a separator 46. An outlet line 48 provided with a valve 50 allows

withdrawal of liquid collected in the separator 46. Gaseous products and entrained liquids from the separator 46 are delivered through a line 52 to the upper end of a condenser coil 54. Cooling means illustrated as a water cooled jacket 56 around the condenser coil 54 cools the gases from separator 46 to a temperature at which the less volatile products of combustion will condense. The mixture of gas and liquid products from the condenser coil 54 is delivered through line 58 to a separator 60. Liquid products collected in separator 60 are discharged through a line 62 provided with a valve 64. Uncondensed gaseous products from separator 60 together with entrained liquids pass through a side outlet line 66 into the bottom of a high voltage electrical precipitator 68 where entrained liquids are removed from the gases and drain through a discharge line 70 into a receiver 72. Liquid products collected in receiver 72 are discharged through a line 74 provided with a valve 76. Gaseous products are discharged from the top of the electrical precipitator 68 through a line 78 into a gas meter 80 which measures the flow rate of non-condensable gaseous products from precipitator 68. Gaseous products from the gas meter 80 are discharged to the atmosphere through line 82.

In preparation for each of the experimental runs, suitably sized rods were inserted through thermocouple wells 36 flush with the inside wall of the combustion tube 24 and one end plate was bolted in position to close one end of the tube. Heating elements 30 were turned on and the entire tube heated to about 200° F. Tar sand was preheated to 200° F. and carefully tamped in place until the tube 24 was full. The other end plate was bolted in position and the rods in the thermocouple wells were driven into the center of the sand and then removed. Thermocouples 34 were inserted through the thermocouple wells 38 and into the center of the sand thus occupying the space created by removal of the rods. The complete assembly 22 was then allowed to cool to room temperature.

With the tube in a vertical position an electric flange heater 84 is heated as rapidly as possible to a temperature sufficiently high to initiate combustion at the air flux used. When this temperature is reached, air is admitted to the tube 24 through the line 18 at the desired rate. Immediately upon contact of the air with the hot tar sand at the bottom of the tube combustion is initiated, and a combustion zone is formed and moves from the bottom to the top of the tube.

At this time there will still be warm oil remaining in the sand in a quantity which depends on the air flux used. The lower the flux used, the greater will be the amount of oil remaining. This oil can then be recovered by a variety of subsequent recovery steps mentioned earlier. However, in the case of the data which will be presented, this oil was recovered by forward combustion. Thus, in case the remaining oil is to be recovered by forward combustion, air is injected in the top of tube 22 through line 18 at a rate suitable to the economic production of oil by that process. This rate need not be the same as that used for the low temperature reverse combustion operation, but as a matter of convenience, it was the same in the experiments which will be reported. Following the forward combustion step, only a clean sand remains in the combustion tube, all hydrocarbon materials having been either recovered or burned in the improved process.

The procedure indicated above was repeated for tar sands from six sources. The curve presented in FIGURE 3 of the drawings is an average of the peak temperatures achieved during twenty of these runs carried out at various values of the air flux and for tar sands from several sources. The data obtained on experimental runs on tar sands from several sources are presented in Table I. Similar results are obtained when the tube 24 is packed with crushed oil shale.

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Table I

| Tar Sand           | Oil Saturation, Wt. Percent Based on Original tar sand | Air Flux, s.c.f./ (hr.) (ft. <sup>2</sup> )—Based on Empty Tube | Average Peak Temp., ° F. |
|--------------------|--------------------------------------------------------|-----------------------------------------------------------------|--------------------------|
| Asphalt Ridge..... | 12.4                                                   | 41.3                                                            | 742                      |
| Do.....            | 11.9                                                   | 72.3                                                            | 928                      |
| Do.....            | 12.6                                                   | 72.3                                                            | 929                      |
| Do.....            | 11.9                                                   | 72.3                                                            | 961                      |
| Do.....            | 11.8                                                   | 72.3                                                            | 963                      |
| Oklahoma.....      | 8.0                                                    | 71.3                                                            | 903                      |
| Do.....            | 8.0                                                    | 35.5                                                            | 716                      |
| Vernal.....        | 7.4                                                    | 44.3                                                            | 760                      |
| Do.....            | 7.2                                                    | 53.7                                                            | 879                      |
| Athabaska.....     | 13.2                                                   | 53.0                                                            | 861                      |
| Do.....            | 12.6                                                   | 13.2                                                            | 565                      |
| Uvalde.....        | 18.7                                                   | 53.9                                                            | 853                      |
| Athabaska.....     | 13.1                                                   | 134                                                             | 1,050                    |
| Dismal Creek.....  | 8.2                                                    | 50.8                                                            | 899                      |
| Athabaska.....     | 13.1                                                   | 55.3                                                            | 888                      |
| Asphalt Ridge..... | 11.4                                                   | 75.3                                                            | 852                      |
| Do.....            | 12.2                                                   | 40.1                                                            | 726                      |
| Do.....            | 11.4                                                   | 38.1                                                            | 733                      |
| Do.....            | 11.2                                                   | 24.1                                                            | 610                      |
| Do.....            | 13.0                                                   | 9.20                                                            | 500                      |

It was found that if the peak temperature reached during the reverse combustion process did not exceed 750° F., that additional liquid hydrocarbon product was obtained upon injection of air after the reverse combustion had proceeded from the outlet to the inlet end of the tar sand.

The plot of the percent of oil recovered against the air flux in FIGURE 4 shows the advantages of this invention in causing increased recovery of oil. The dotted line to the left of the intersection of the lines in FIGURE 4 indicates the total recovery of oil and the solid line to the left of the intersection indicates the recovery during the low temperature reverse combustion step. It will be noted that at air fluxes causing temperatures below about 750° F. (corresponding to fluxes of about 40 standard cubic feet per square foot per hour) additional oil was recovered upon injection of air after reverse combustion had ceased. In the run at the air flux of approximately 9 standard cubic feet per square foot per hour, the recovery was increased from 17% to 59% of the oil in the tar sand. In contrast, in runs at air fluxes in excess of 40 standard cubic feet per square foot per hour, no additional oil was recovered after the reverse combustion had proceeded from the outlet to the inlet end of the combustion tubing.

Another advantage of this invention is shown in FIGURE 5, where the ratio of air injected to oil recovered is plotted against the air flux. The dotted line to the left of the intersection of the lines in FIGURE 5 indicates the over-all air-oil ratio for a process consisting of low temperature reverse combustion followed by a forward combustion step. The solid line to the left of the intersection of the lines in FIGURE 5 indicates the air-oil ratio during the low temperature reverse combustion step. It will be noted that at air fluxes causing temperatures below about 750° F. (corresponding to fluxes of about 40 standard cubic feet per square foot per hour) upon injection of air after reverse combustion had ceased, a sufficiently large decrease in the air-oil ratio was obtained that the over-all air-oil ratio was lower than could ever be achieved by a recovery process wherein the first step was conventional reverse combustion.

The curve in FIGURE 3 shows the relation between the peak temperature attained and the air flux at substantially atmospheric pressure. Higher pressures result in lower peak temperatures for a given air flux. For example, an air flux of 55 standard cubic feet per square foot per hour passed through a tar sand under a pressure of 450 pounds per square inch, resulted in a peak temperature of 550° F. At atmospheric pressure the same air flux would result in a temperature of approximately 855° F. However, an air flux less than 40 standard cubic feet per square foot per hour in a reverse combustion

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process would allow recovery of additional oil from the formation after the reverse combustion process is completed in a reverse combustion process performed at high pressures as well as low pressures because of the lower peak temperatures reached.

One well structure adapted for carrying out the process of this invention is illustrated in FIGURE 2 of the drawings. Referring to that figure, a well indicated generally by reference numeral 90 is drilled through an oil-bearing formation 92 between a cap rock 94 and an underlying base rock 96 to a total depth 98. Casing 100 is run into the well and cemented in place by a sheath 102 of cement in accordance with the usual techniques for thermal recovery processes. The casing 100 and cement sheath 102 are perforated at 104 near the upper limits of the pay zone 92 and at 106 near the bottom of the pay zone.

A large substantially horizontal radial fracture 108 is made in the lower portion of the pay zone. A similar fracture 110 is made near the upper limit of the pay zone. A packer 112 is run into the casing 100 and set at a position between the upper perforations 104 and lower perforations 106. Tubing 114 extends from the well head through packer 112 and opens at its lower end within the casing adjacent the perforations 106. Tubing 114 extends upwardly through a cap 116 closing the upper end of the well and is connected with a line 118 for delivery of oil produced from the well. An air supply line 120 extends through the cap 116 and communicates with the annular space 122 between the casing 100 and the tubing 114.

In carrying out the process of this invention, a suitable burner, not shown, is positioned in the well adjacent the perforations 106. A mixture of a fuel and air is burned adjacent the perforations 106 and the products of combustion forced into the fracture 110 to heat the formation around fracture 108 to a temperature high enough to initiate reverse combustion. Air is introduced into the well through line 120 and discharged through perforations 104 into fracture 110. The air flows downwardly through the pay zone 92 to cause in-situ combustion of oil to begin in the hot formation adjacent the fracture 108. As the injection of air is continued, the combustion front moves upwardly countercurrent to the flow of air, and oil produced from the formation is removed through line 114. Injection of air is continued at a rate controlled to maintain the temperature in the formation below 750° F. The substantially linear flow from the upper fracture to the lower fracture facilitates control of the air flux. When the combustion front reaches the upper fracture 110, the flow of air can be stopped and production of the hot oil remaining in the formation obtained by a gas repressuring process, a water injection process, or by gravity drainage. It is preferred, however, to follow the low temperature reverse combustion step by a forward combustion process by injection of additional air, thus effectively removing substantially all of the remaining oil from the heated pay zone. Any gravity drainage that may occur in the pay zone favors increased recovery of the oil when the production is delivered into the lower fracture during both the low temperature reverse combustion and subsequent recovery steps. The fractures through which air is injected and the production recovered can be reversed, but the advantage of gravity drainage is not obtained if the direction of flow is reversed.

Ignition of oil in the formation is accomplished by heating the formation to a temperature sufficiently high that when contacted with an oxygen-containing gas ignition will occur. A preferred method is to inject air into the formation at the injection well until it can be produced at the production well with an oxygen content high enough to cause ignition of oil in the formation when the formation is heated. Air injection is then stopped and a gas burner ignited in the production well. The products of combustion are displaced into the formation

until the formation is heated for a radial distance of at least a few inches from the borehole of the production well to a temperature higher than the peak temperature attained in a low temperature reverse combustion process at the air flux existing in the heated zone when air injection is resumed. The burner is then removed from the production well and air again injected into the formation at the injection well. Ignition occurs as air reaches the heated zone in the formation.

If an electric heater is used, the formation surrounding the production well is heated by conduction or by gases passed over the heater and into the formation. If air is passed over the electric heater, forward combustion may be initiated at the production well. Forward combustion can be continued until an injection pressure approaching the overburden pressure on the formation is attained. The injection of air at the production well is then stopped and air is injected at the injection well. When the air from the injection well reaches the zone of forward combustion, the combustion is converted to reverse combustion. After reverse combustion has started, the air flux is adjusted to cause the desired flow temperature reverse combustion.

The process of this invention can be used in other well arrangements. For example, one well may be used as an input well and an adjacent well as a production well. Another arrangement that can be used effectively is to use wells in one row as injection wells and in an adjacent row as production wells. The location at which oil is delivered from the formation in channels for delivery to the well head and recovery is generally referred to as the production well in the description of this invention. It is to be understood that the invention is not limited to a process using separate injection and production wells and that the term "production well" includes within its scope any production zone spaced from the injection zone through which oil is produced from the formation into channels suitable for delivery of the oil, gas, and combustion products to the well head.

In a specific example of the production of oil by this invention, a well is drilled to a total depth of 575 feet through a pay zone in the interval of 530 to 565 feet. Casing is run into the well to total depth and cemented by conventional practice. The casing and surrounding cement sheath are then severed by a ring shaped charge at a depth of 560 feet and again at a depth of 535 feet. A packer is set in the casing between the two levels at which the casing is cut. The formation is then fractured through the lower opening in the casing to form a horizontal fracture having an estimated radius of 100 feet, and the fracture is propped open with coarse sand. With the packer in place but closed to isolate the lower fracture, a horizontal fracture having an estimated radius of 100 feet is formed through the opening in the casing at a depth of 535 feet. The upper fracture is also propped open with coarse sand.

A burner is run through the packer to a position adjacent the lower fracture and a combustible mixture of lease gas and air delivered to the burner at a rate of 2000 cubic feet of lease gas per hour and burned below the packer. The hot products of combustion are displaced from the borehole into the lower fracture to heat the formation adjacent the fracture to a temperature estimated to range between 1000° F. and 750° F. The burner is pulled from the hole and tubing run through

the packer to a position with its lower end opening adjacent the lower fracture.

Air is then displaced into the upper fracture at a rate of 600,000 standard cubic feet per hour causing an air flux of approximately 20 standard cubic feet per square foot per hour at the combustion front between the upper and lower fracture. When the air contacts the heated formation, low temperature reverse combustion of the oil in the formation is initiated. The injection of air is continued to cause the combustion front to move upwardly to the upper fracture. A mixture of hot oil, gas, and combustion products is delivered through the bottom fracture into the borehole and lifted through the tubing to the well head.

The process of this invention results in the production of an oil of relatively low specific gravity. The production of low specific gravity oil during the low temperature reverse combustion process is believed to be attributable to an efficient fractionation of light ends out of the oil by the advancing thermal wave in conjunction with the predominantly inert gas atmosphere provided by the nitrogen content of injected air together with products of combustion which are accumulating in concentration as the temperature increases. The oil produced in the low temperature reverse combustion is frequently clear and amber in color rather than the dark oil produced in the reverse combustion processes of the prior art.

In the specification and claim of this application, the term "low temperature reverse combustion" is used to designate a reverse combustion process in which the peak temperature is low enough that fluid oil remains in the formation after completion of the reverse combustion process. That fluid oil is hot and can then be recovered from the hot formation in a subsequent recovery step and thereby increase the amount of oil recovered from the formation.

We claim:

An in-situ combustion process for the recovery of oil from an oil-bearing subsurface formation penetrated by an injection well and a production well spaced from the injection well, comprising displacing air down the injection well into the oil-bearing formation and through the oil-bearing formation to the production well, heating oil in the oil-bearing formation adjacent the production well to a temperature whereby said oil ignites upon contact with the air displaced through the formation, continuing the displacement of air into the formation at a rate controlled to give an air flux at the combustion front less than about 40 std. cu. ft./sq. ft./hr. to cause reverse combustion to proceed at a temperature below approximately 750° F. from the production well to the injection well, discontinuing the displacement of air down the injection well and into the formation upon arrival of the reverse combustion front at the injection well, thereafter displacing water down the injection well and into the formation to drive oil present in the formation to the production well, and lifting oil through the production well to the surface.

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