June 23, 1964 S. P. EWING ETAL 3,138,202

THERMAL OIL RECOVERY PROCESS

Filed Nov. 17, 1960 3 Sheets-Sheet 1

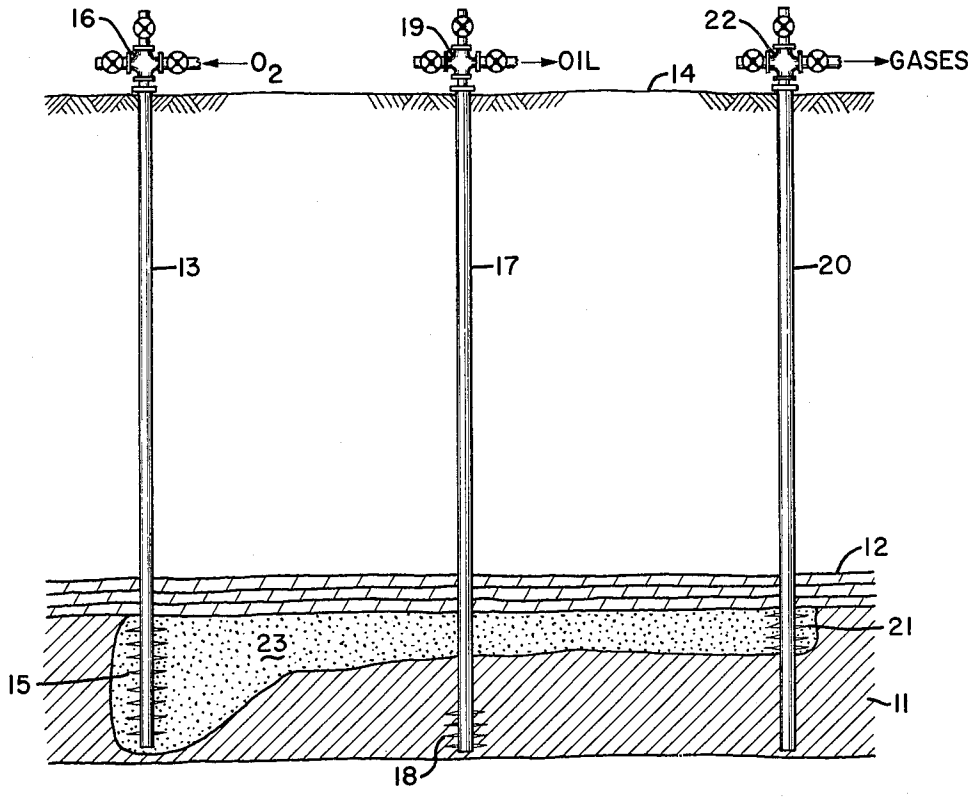


FIG. 1

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3 Sheets-Sheet 2

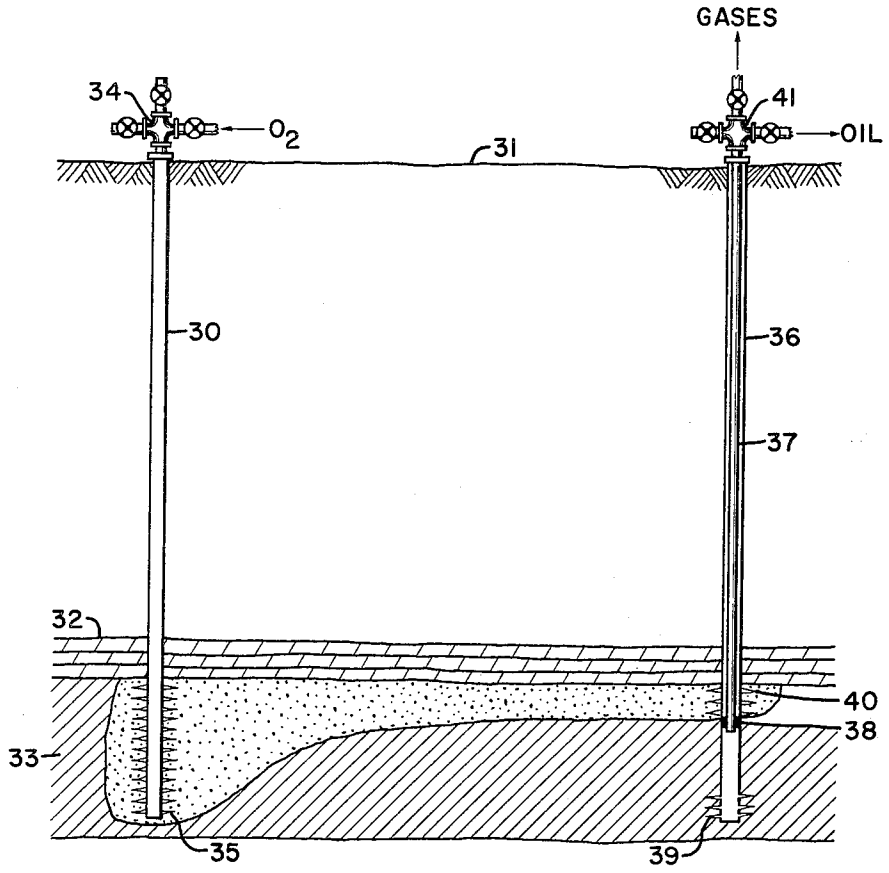


FIG. 2

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THERMAL OIL RECOVERY PROCESS

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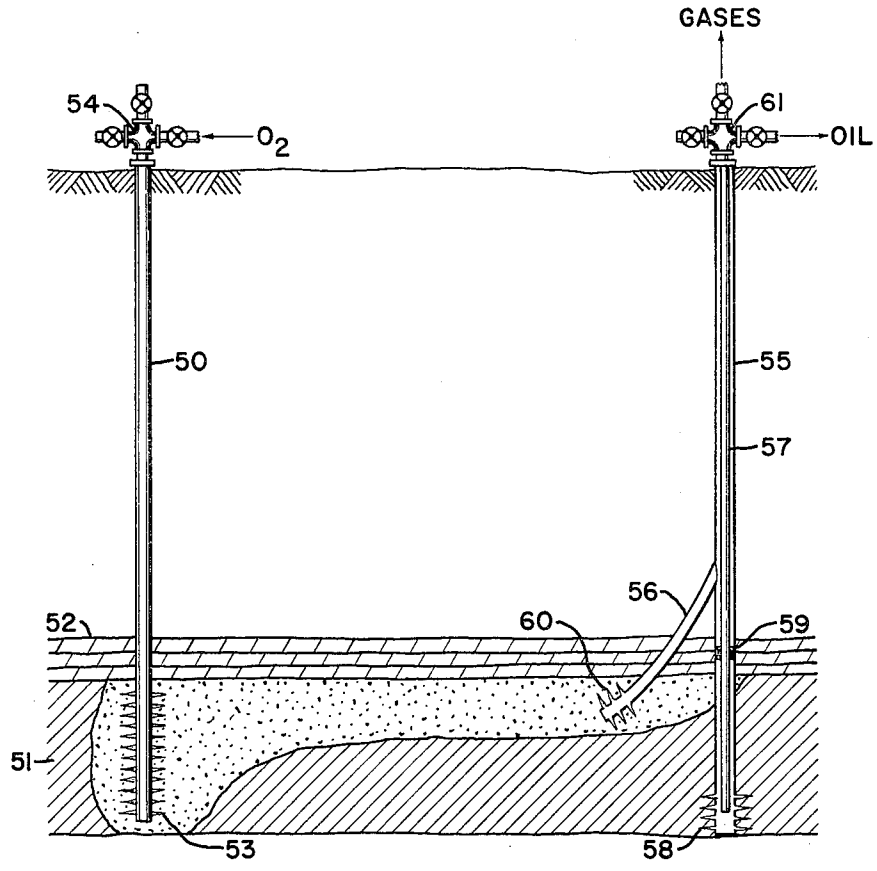


FIG. 3

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3,138,202

THERMAL OIL RECOVERY PROCESS

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5 Claims. (Cl. 166—2)

The present invention relates to thermal methods for recovering crude oil from subsurface oil-bearing reservoirs and more particularly relates to an improved in situ combustion oil recovering process wherein production well maintenance costs are substantially lower than those incurred in conventional in situ combustion operations. In still greater particularity, the invention relates to an oil recovery process in which crude oil and gases resulting from in situ combusion are separately recovered from the reservoir in order to minimize combustion and high temperature corrosion in the production well.

Methods for the recovery of crude oil from subsurface oil-bearing reservoirs by the in situ combustion of a portion of the oil contained therein have received increasing attention in recent years. Such methods basically involve the establishment of a combustion front in an oil-bearing reservoir in the vicinity of one or more injection wells and the subsequent introduction of an oxygen-containing gas through the injection well in order to support combustion and move the combustion front through the reservoir toward one or more production wells. As the combustion front is thus advanced, heat liberated by the combustion of fuel in the reservior results in the vaporization of oil from a high temperature zone which precedes the combustion front. Cracking of a portion of the oil and the formation of coke which serves as fuel for the process also occur. The oil vapors which are thus formed are carried forward with the combustion products and are condensed in cooler sections of the reservoir well in advance of the combustion front. Heat transferred from hot gases and vapors to oil in the cooler sections reduces the viscosity of the oil and facilitates its movement into the production well. A mixture of oil and gases is withdrawn from the well and is subsequently separated to permit recovery of the hydrocarbons contained therein.

Although in situ combustion shows considerable promise of providing a means for recovering oil from subsurface reservoirs which is more economical than processes utilized in the past, there are certain practical difficulties which have limited its application to date. Combustion of the oil and high temperature corrosion at the production well are among the most serious of these. Laboratory work and field tests have shown that the oxygen injected into the reservoir during such an operation is only partially utilized for combustion and that the gases which flow into the production well normally contain oxygen in significant quantities. As the combustion front nears the well, the temperature of these gases increases. When the wellbore temperature reaches the ignition temperature of the oil flowing into it, combustion occurs. This further elevates the wellbore temperature and may result in rapid burning-out of the casing, tubing, pump and other equipment in the wellbore. Severe corrosion takes place. It is therefore necessary to interrupt the recovery operation at frequent intervals and repair or replace the tubing and other equipment. Experience has shown that the maintenance costs thus incurred are often so high that the economics of the entire operation become marginal.

It has been the practice in the past to inject a stream of water into the annular space between the tubing and casing in the production well in order to cool the wellbore and mitigate the difficulties outlined above. This technique is only partially effective. In shallow reservoirs

where the flowing back pressures opposite the producing formation are low, the injected water vaporizes at temperatures below the ignition temperature of the oil. Heat transferred to the water as it vaporizes serves to cool the wellbore. If sufficient water is injected, the temperature can be held below the oil ignition temperature and thus combustion and severe corrosion can be avoided. The quantities of water required are large and hence the cost of cooling the wellbore in this manner is high. In deeper reservoirs where flowing back pressures in excess of about 250 pounds per square inch are encountered, the vaporization temperature of water exceeds the oil ignition temperature. The oil can therefore be cooled below the ignition temperature only through the transfer of sensible heat to the injected water. The amount of water required under these circumstances is much greater than in the case of relatively shallow production wells and thus water cooling is even less attractive from an economics standpoint. The use of cooling fluids which have higher vapor pressures than water has been considered. Such fluids in general have considerably lower latent heats of vaporization than water and are prohibitively expensive. To date no wholly satisfactory method for reducing maintenance costs at production wells during in situ combustion has been found.

The present invention provides a new and improved method for carrying out in situ combustion oil recovery operations which largely obviates the difficulties described in the preceding paragraphs. In accordance with the invention, it has now been found that the combustion front normally progresses along the upper boundary of the reservoir during an in situ combustion oil recovery operation and that this fact can be utilized to permit separate recovery of the crude oil and the gases produced during in situ combustion. By producing oil from a point near the bottom of the reservoir and separately producing gases from the upper section away from the oil recovery zone, contact between the oil and the free oxygen in the production well can be avoided. This prevents combustion in the production well and materially reduces the cost of maintaining pumps, tubing, casing and other production well equipment.

The process of the invention may be carried out using separate wells for the recovery of oil and gases or may instead utilize wells completed at two different levels to permit the production of oil through a string of tubing below a heat-resistant packer and the production of gases through the annular space above the packer. In either case, the segregation of the oil and gases due to the difference in their densities and the high gas mobility in burned-out sections of the reservoir is utilized to permit their separate recovery. Little or no gas is recovered with the product oil and hence little or no combustion of the product oil takes place in the wellbore. Wellbore temperatures are lower than they would be if combustion occurred in the wellbores and thus corrosion difficulties are mitigated. The gases are recovered at relatively high pressures and can be reinjected to take advantage of the oxygen and heat contained therein without incurring high recycle compression costs. The invention therefore permits substantial reduction in the cost of in situ combustion operations and may in some cases make such operations attractive in reservoirs where economic considerations would otherwise dictate against in situ combustion.

The nature and objects of the invention can best be understood by referring to the following detailed description of several embodiments of the process and to the accompanying drawing, in which:

FIGURE 1 depicts an situ combustion operation wherein separate wells are utilized for the recovery of oil and the recovery of gases from a subsurface reservoir;

FIGURE 2 illustrates separate oil and gas production through a common well in which the casing is perforated above and below a heat-resistant packer penetrated by a tubing string; and,

FIGURE 3 shows the use of a well completed at two different levels by whipstocking in order to permit the separate recovery of oil and gases from the reservoir.

Turning now to FIGURE 1 of the drawing, reference numeral **11** designates a subsurface oil-bearing formation bounded on the top by an oil-impervious caprock **12**. The bounding strata underlying the oil-bearing zone are not shown. An injection well **13** has been drilled into the oil sand from the earth's surface **14** and has been cased in the usual manner. A gun perforator, an abrasive jet or other conventional tool has been used to perforate the well opposite the oil sand. The injection well perforations are indicated by reference numeral **15**. A conventional wellhead **16** provided with connections through which fluids may be introduced into the injection well has been provided on the surface. Oil production well **17** has been drilled into the oil sand from a point on the surface located about 50 feet to about 1000 feet or more from the injection well. The oil production well has been cased and perforated a short distance above the bottom of the oil-bearing zone. The perforations are indicated by reference numeral **18**. Wellhead **19** and conventional surface facilities, not shown, have been provided for recovering oil from the production well. Gas production well **20** has been drilled into the oil sand at a point removed from the oil production well. The distance separating the oil production well and the gas production well will in part depend upon the particular recovery pattern utilized and may range from a few feet to 1000 feet or more. It is normally preferred that the gas production wells lie some distance beyond the oil production wells away from the injection well. The gas production well has been cased and perforations **21** are located near the upper boundary of the oil-bearing formation. Wellhead **22** provides for the recovery of gases from well **20**.

Although only three wells are shown in FIGURE 1 of the drawing, it will be recognized that the process of the invention will normally be carried out with a plurality of injection wells, a plurality of oil production wells and a plurality of gas production wells. These wells may be arranged in any of a number of conventional patterns, including the five spot, the seven spot, the nine spot and the line drive patterns. It is not necessary that the number of oil production and gas production wells be the same. In many cases, a larger number of oil wells than gas wells will be found desirable.

In carrying out an in situ combustion operation in the oil-bearing reservoir shown in FIGURE 1 of the drawing, a combustion front is first established in the reservoir in the vicinity of the injection well **13**. It is normally preferred to heat the formation surrounding the well to a temperature in the range between about 450° F. and about 1200° F. and then inject oxygen or an oxygen-containing gas in order to establish the combustion front. In some deep reservoirs, however, combustion may take place spontaneously upon the injection of oxygen and hence preliminary heating of the formation is not required. There are a number of known methods for heating the strata surrounding the injection wells which may be utilized. These include the injection of high temperature combustion products into the reservoir from the surface, the use of an electrical device to ignite a mixture of fuel gas and oxygen in the injection well opposite the producing zone, the injection of a mixture of linseed oil and cobalt naphthenate or similar pyrophoric materials and a stream of combustion supporting gas into the reservoir, and the use of an electrical or gas-fired heater placed opposite the oil-bearing formation. The injection of a pyrophoric material and oxygen is a preferred method and is the system normally employed where spontaneous combustion does not occur.

Once the formation in the vicinity of the injection well has been heated to a temperature in excess of the ignition temperature of the hydrocarbons contained in the formation, the combustion front is established by injecting oxygen through the injection well into the formation. Air, air enriched with oxygen or pure oxygen obtained from a tonnage oxygen plant located on the surface may be employed as the injection gas. The injected gas cools the wellbore and transfers heat into the oil-bearing formation surrounding it. After the wellbore has been cooled below the ignition temperature of the oil or after all of the oil in the formation immediately adjacent the injection well has been consumed, the combustion front thus established can be propagated through the reservoir toward the production wells. The injected gas progresses out into the formation from the injection well and is preheated to a temperature above the ignition temperature of the oil in the formation as it passes through hot burned-out zones of the reservoir behind the combustion front. The preheated air which comes in contact with residual fuel at the leading edge of the front advances the front, generating heat and combustion gases which promote the recovery of the oil in the reservoir.

As the combustion front is thus advanced, the hot gases normally rise in the reservoir because of the oil-gas density difference and the high mobility of the gases in the burned-out rock. The oil displaced by the gases in advance of the combustion front drains downwardly into the lower section of the reservoir. This rapidly leads to the establishment of a burned-out zone near the upper boundary of the reservoir and a lower zone containing oil. Once such a system has been established, it tends to perpetuate itself. The combustion front proceeds along the top of the reservoir and thus contact between oxygen and oil in the lower zones takes place primarily through gaseous diffusion. This phenomenon is generally referred to as overburning. The overburned zone in FIGURE 1 of the drawing is designated by reference numeral **23**. Due to overburning, the oxygen which when mixed with oil in the wellbore gives rise to well maintenance problems is segregated at the top of the formation. The oxygen-containing gases are recovered through perforations **21** in gas production well **20**. Since the gases are essentially free of oil, combustion does not take place within the gas production well. The gas temperatures remain below the equipment limiting temperatures. Less cooling of the well than would ordinarily be required is necessary.

The oil heated as a result of combustion taking place at the lower edge of burned-out zone **23** drains downwardly in the reservoir and is recovered through perforations **18** in oil production well **20**, oil production well **17** can be flowed if desired. Thereafter, well **17** is pumped to lift the oil to the surface. Since comparatively little gas is recovered with the oil and since its viscosity is relatively low because of the elevated temperature, pumping poses no serious difficulties. The oil is recovered essentially free of oxygen and hence combustion does not take place in the wellbore. A water quench, not shown in FIGURE 1, may be used to cool the oil string. Only a relatively small amount of water need be used.

The recovery of oil and gases from the reservoir through separate wells as shown in FIGURE 1 of the drawing permits operation of the in situ combustion process without the production well maintenance problems which characterize most in situ combustion operations. Field tests have shown that breakthrough of the combustion front at the production well often occurs in conventional operations after only about 20 percent or less of the ultimate oil recovery has been attained. It is frequently necessary to shut down the process at that point because of the high cost of maintaining and replacing production

well equipment. By taking advantage of the overburning phenomenon to recover the oil and gases separately, this high cost can largely be avoided and substantially complete oil recovery can be obtained.

As pointed out heretofore, the gases recovered from the gas production well **20** may be recycled to the injection well **13** in order to utilize their heat and oxygen contents. After breakthrough of the combustion front at the gas production well, the pressure drop as the gases flow through the burned-out rock is relatively low and hence only moderate compression is required to reach the injection pressure level. Because of the relatively high oxygen content of the gases, the amount of makeup oxygen which must be added is comparatively small. The recycle of gases in this manner offsets the pumping costs incurred due to the loss of the lifting capacity of the separately produced gases.

In a modification of the process illustrated by FIGURE 1 of the drawing, separate production of the oil and gases through wells **17** and **20** is continued until breakthrough of the combustion occurs at gas production well **20** and the amount of gas which must be circulated through the reservoir becomes high in terms of the amount of oil recovered. At that point, gas injection may be halted in order to terminate combustion. Injection well **13** may then be converted into a gas production well. Gas well **20** may be adapted for use as an injection well by plugging perforations **21** and forming a new set of perforations near the bottom of the reservoir. Oxygen containing gas may then be injected into the reservoir through well **20**. Because of the elevated temperature of the oil in the reservoir, ignition will occur and a new combustion front will be established. Oil may again be recovered through well **17** and gases may be withdrawn through well **13**. The oxygen thus injected after breakthrough of the initial combustion front will be utilized with somewhat greater efficiency than it would be if it were merely circulated through the burned-out zone created by the first combustion front. The second front will eventually break through into the burned-out zone at the top of the reservoir due to overburning, however, and in time the oxygen utilization will therefore decline to that which would have been obtained if the injection and gas production wells had not been shifted. It will be apparent that additional shifting of injection and production wells may be carried out in reservoirs containing a plurality of injection wells, oil production wells and gas production wells in order to further increase the recovery rate and improve oxygen utilization.

FIGURE 2 of the drawing illustrates a further embodiment of the invention wherein oil and gases are separately recovered through a common production well. Injection well **30** in FIGURE 2 has been drilled from the surface **31** through cap rock **32** into oil sand **33**. The well has been cased and fitted with wellhead **34**. Perforations **35** have been made opposite the oil-bearing zones. The common production well is spaced at a distance of from about 50 feet to about 1000 feet or more from the injection well. If contains an outer string of casing **36** and an inner string of tubing **37**. The tubing extends a short distance into the producing zone and terminates below a heat-resistant packer of absestos or similar material or an annular cement plug **38**. Perforations **39** near the bottom of the oil zone below the packer permit the production of oil from the lower section of the reservoir through the tubing. Perforations **40** above the packer permit the production of gases from the upper part of the sand through the annular space between the tubing and casing. The two streams are separately recovered on the surface through wellhead **41** and appropriate auxiliary equipment not shown in FIGURE 2.

The in situ combustion operation is carried out in the reservoir shown in FIGURE 2 in a manner similar to that earlier described. After the combustion front has been established, it is advanced through the reservoir by injecting an oxygen-containing gas through injection well **30**. Due to overburning, the front will normal progress through the reservoir near its upper boundary. Gases produced from the upper zone flow through the annular space between tubing **37** and casing **36** in the production well. Oil is simultaneously produced through the tubing from the lower section of the reservoir. Separate production of the two in this manner avoids combustion within the production well and thus simplifies production well maintenance problems. A water quench not shown in the drawing removes heat from the wellbore and further reduces corrosion and attendant difficulties.

Still another embodiment of the invention is shown in FIGURE 3 of the drawing. In the reservoir depicted in FIGURE 3, injection well **50** has been completed in the manner earlier described, the perforations opposite the oil-bearing sand **51** below cap rock **52** being indicated by reference numeral **53**. Wellhead **54** permits the introduction of oxygen into the injection well. The production well **55** had been completed at two levels in the reservoir by drilling a lateral extension **56** with conventional whipstocking equipment. Tubing **57** extends downwardly in the well to a point near the bottom of the reservoir where perforations **58** are located. A heat-resistant packer or annular cement plug **59** is located in the well about the tubing above the upper boundary of the reservoir and below extension **56**. Perforations **60** are provided in the extension well. Wellhead **61** permits separate recovery of the oil and produced gases at the surface.

In carrying out in situ combustion in the reservoir illustrated in FIGURE 3 of the drawing, gases are produced from the upper part of the reservoir through perforations **60** and extension well **56** and are conveyed to the surface through the annular space between the casing and tubing **57**. Oil is recovered from near the bottom of the reservoir through perforations **58** and tubing **57**. Again, separate production of the oil and oxygen-containing gases precludes combustion within the production well so that maintenance of the well is less expensive than in the conventional in situ combustion operation.

It will be apparent that the invention is not necessarily limited to recovery operations where overburning takes place in the manner shown in the drawing. Even though the combustion front proceeds through the reservoir in a more or less uniform manner, some gravity segregation of the oil and gaseous products takes place. Production from two separate points near the top and the bottom of the reservoir materially reduces the amount of oxygen recovered with the oil. This reduces the likelihood that combustion will occur within the production well. Since the amount of oil remaining in the reservoir following breakthrough of the combustion front is much less where overburning does not occur, however, the operation can be terminated sooner and hence the economic incentive for separately recovering oil and gases is less than in a reservoir where overburning and resultant early breakthrough of the combustion front occur.

Many variations in the operation of in situ combustion processes wherein the oil and gas are separately recovered from different levels in the reservoir are possible. In a reservoir such as that depicted in FIGURE 1 of the drawing wherein pronounced overburning does not take place, for example, both wells can be produced simultaneously until the combustion front breaks through at one of the wells. If breakthrough occurs first in the ultimate gas well completed near the top of the oil-bearing formation, the gas well may be shut in temporarily and the oil well may be produced until the sand is burned clean around the bottom of the gas well. The gas well may then be opened up and both wells may be produced simultaneously again. If breakthrough should occur at the oil well near the bottom of the reservoir before it takes place at the higher gas well, the oil well may be shut in and the gas well may be produced in order to force the burning front up to the gas well. Oil will drain downwardly in

the reservoir and resaturate the sand around the oil well. After this occurs, both wells may be produced simultaneously in the manner earlier described. Similar measures may in some cases be advantageous in reservoirs such as those depicted in FIGURES 2 and 3 of the drawing. These and other variations will be readily apparent to those skilled in the art.

What is claimed is:

1. A process for the recovery of oil from a subterranean oil-bearing reservoir which comprises:

(*a*) establishing a combustion front within said reservoir in the vicinity of at least one injection well penetrating said reservoir;

(*b*) introducing an oxygen-containing gas into said reservoir through said injection well to advance said combustion front in a substantially horizontal direction toward at least one production well penetrating said reservoir at a distance from said production well;

(*c*) withdrawing oil from said reservoir at a point in the lower part of said reservoir and conducting said oil to the earth's surface through said production well without contacting high temperature combustion gases; and

(*d*) withdrawing gases from said reservoir at a point in the upper part of said reservoir remote from said injection well and conducting said gases to the earth's surface without contacting said oil in said production well.

2. A process as defined by claim 1 wherein said oil and said gases are conducted to the surface through separate conduits isolated from one another in said production well.

3. A process as defined by claim 1 wherein said gases are conducted to the surface through a separate well located at a distance from said production well.

4. A process for the recovery of oil from a subterranean oil-bearing reservoir which comprises:

(*a*) establishing a combustion front within said reservoir in the vicinity of at least one injection well penetrating said reservoir;

(*b*) introducing an oxygen-containing gas into said reservoir through said injection well to advance said combustion front toward at least one production well penetrating said reservoir at a distance from said injection well;

(*c*) withdrawing oil from said reservoir at a point in the lower part of said reservoir and conducting said oil to the earth's surface through said production well without contacting high temperature combustion gases;

(*d*) withdrawing gases from said reservoir at a point in the upper part of said reservoir and conducting said gases to the earth's surface through a separate gas well located at a distance from said injection and production well;

(*e*) discontinuing the injection of said oxygen-containing gas into said reservoir through said injection well following breakthrough of said combustion front at said gas well;

(*f*) converting said injection well into a gas production well;

(*g*) converting said gas well into an injection well;

(*h*) injecting an oxygen-containing gas into the lower part of said reservoir through the converted gas well;

(*i*) withdrawing gases from said reservoir through the converted injection well; and

(*j*) again recovering oil from said reservoir through said production well.

5. A process for the recovery of oil from a subterranean oil-bearing reservoir which comprises:

(*a*) establish a combustion front within said reservoir in the vicinity of at least one injection well penetrating said reservoir;

(*b*) introducing an oxygen-containing gas into said reservoir to support combustion and advance said combustion front through said reservoir;

(*c*) recovering gases from said reservoir through at least one gas production well completed in the upper part of said reservoir at a distance from said injection well;

(*d*) recovering oil from said reservoir through at least one oil production well completed in the lower part of said reservoir at a distance from said injection well;

(*e*) continuing the simultaneous production of fluids from said gas production well and said oil production well until said combustion front breaks through at one of said wells;

(*f*) shutting in the well at which breakthrough of said combustion front occurs and producing said other well until breakthrough of said combustion front occurs at said other well; and

(*g*) thereafter producing said production wells simultaneously.

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