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3,239,405

UNDERGROUND COMBUSTION PROCESS

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This is a continuation-in-part of my co-pending application, U.S. 833,701, filed August 14, 1959, now abandoned.

The present invention relates to an improved method for recovering valuable products such as petroleum from underground reservoirs thereof by means of combustion. More particularly, it is concerned with a novel method of controlling the reservoir temperature level in a reverse burning operation which may be followed by forward combustion and conducting the latter operation in such a way as to require less oxygen than is needed in conventional forward combustion. Specifically, my invention is directed to control of reservoir temperature during reverse burning and then after this step, but before initiating forward combustion, injecting into the hot formation a suitable fluid hereinafter defined.

While the present description emphasizes the applicability of the process of my invention to the recovery of oil from underground reservoirs of petroleum tars and viscous crudes, e.g., having an API gravity of not more than about 10°, the principles taught herein are intended to pertain likewise to the recovery of oil from oil shale and to the gasification of coal. In either of these types of carbonaceous deposits, if the native permeability thereof is insufficient, permeability may be induced in a known manner. The term "carbonaceous" as used herein is intended to refer to materials comprising either free or combined carbon.

Some of the largest known liquid petroleum deposits in the world are the Athabasca tar sands located in northern Alberta. It has been estimated that this area alone contains approximately three hundred billion barrels of oil. Other huge deposits of a similar nature are to be found in areas of the United States and in Venezuela. Owing, however, to the highly viscous nature of these deposits, their production has presented an extremely difficult problem. Numerous proposals have been made in an effort to recover such material including, for example, processes involving mining the tar and thereafter centrifuging it in the presence of certain solvents and surface active agents to separate the tar from the sand with which it is associated. Also, attempts have been made to recover oil from the tar sand by subjecting the latter to treatment with hot water and separating the resulting upper oil layer. These and other methods which have been used, however, all require large labor and capital expenditures rendering such procedures economically unattractive.

Underground combustion as a means of recovering deposits of this type has likewise been suggested. In general, however, the very high differential pressures that must be applied between input and producing wells to recover the oil presents an extremely difficult problem. Frequently, the pressures that must be applied to shallow reservoirs of low permeability, i.e., less than 100 millidarcies, are higher than can be applied economically and/or without causing uncontrolled fracturing of the formation which would lead to channeling and bypassing.

Conventional underground combustion, i.e., an operation in which the combustion zone is propagated from a point near the face of an injection well toward a producing well, is impossible with heavy viscous hydrocarbons of the type contemplated herein. This is for the

reason that the hot portion of the reservoir rock yielding the heavy oil lies between the injection well and the burning zone. In this zone the viscosity of the oil is at a minimum; however, as the pressure of the system forces the oil toward the producing well, the oil decreases in temperature to that of the unburned portion of the reservoir. Eventually, resistance to flow through the reservoir to the producing well becomes so great that combustion can no longer continue because it is impossible to supply air at a satisfactory rate to the burning zone.

In U.S. Patent 2,793,696 to Morse, a process is described for the recovery of oil by means of an underground combustion process in which conditions are provided such that the combustion zone travels toward the injection well—countercurrent to the flow of the air through the reservoir. This method is ordinarily referred to as "reverse burning" or "reverse combustion." While this procedure has been employed on a limited scale to recover oil under conditions of low reservoir permeability, it has not met unqualified success. Moreover, in accordance with the teachings of the Morse patent, once the combustion zone has passed through the formation from the production well to the injection well, very little, if any, residual oil or tar remains in recoverable form. Actually, there may be some cases where the nature of the reservoir oil is such that substantially all of it distills and/or is cracked. However, where the oil is so high boiling that none or very little of it distills or is cracked at the temperatures reached by reverse burning, such process is ineffective.

The process of my invention is primarily applicable to reservoirs having a low effective initial or native permeability. By the expression "low effective initial permeability," I mean a formation in which conventional forward combustion alone cannot be carried out owing to the fact that the oil temporarily reduced in viscosity in the combustion zone increases in viscosity when it contacts cold reservoir rock on its way to the producing well and hence its resistance to flow through the rock becomes so great that it is either uneconomical or impossible to continue air injection. Stated otherwise, forward combustion alone is considered feasible only when the flow capacity, i.e., the product obtained by multiplying the permeability by thickness of the reservoir in feet, of the reservoir in millidarcy feet is greater than about 30 times the oil viscosity in centipoises. The aforesaid expression, as applied to situations where reverse combustion alone cannot be used to recover oil in commercial quantities, refers to reservoirs where the maximum air injection rate is insufficient to produce a combustion zone temperature of about 800° F.

Actually, the process of my invention may be employed to advantage in reservoirs having an initial effective permeability so low that substantially none of the hydrocarbon in place is distilled or cracked during reverse combustion. For example, in tar sands in which the initial effective permeability is frequently so low that the maximum amount of air injected results in a peak temperature of not more than about 300° or 400° F., no oil is produced during the reverse combustion phase of the process. However, on following this step with forward combustion, at combustion zone temperature ranging from about 1000° to about 2000° F., economical oil recoveries are realized. Such results are made possible because in the reverse burning step the reservoir rock is heated and the viscosity of the hydrocarbon in place is greatly reduced. Forward combustion can then be used to force the oil of reduced viscosity through the heated reservoir without the difficulties referred to above which are normally encountered in attempts to

recover heavy oils by the use of forward combustion alone.

More recently it has been observed that at practical air injection rates and elevated pressures, reverse combustion alone does not look promising as a means of recovering oil in economic amounts from Athabasca tar sands or equivalent sources. In reservoirs of this kind, temperatures of the order of 400° to 500° F. are seldom exceeded. However, such temperatures are adequate to lower the viscosity of the oil or tar sufficiently so that these reservoirs can be produced efficiently by means of forward combustion methods. One outstanding difference between forward combustion operations of this type and conventional forward combustion is that in the former case there is no water present. Likewise, where forward combustion is effected after reverse combustion the entire reservoir is already at a sufficiently high temperature that ignition can be accomplished on contact of the hydrocarbons with air.

Where conditions permit successful forward combustion, not preceded by reverse burning, the factors largely responsible for such success are the simultaneous gas and water drives accompanying the process. Displacement of oil ahead of the combustion zone is generally so efficient that essentially only residual or bypassed oil is left to be contacted by the combustion zone. Part of this oil is vaporized and the remainder is coked and burned. The amount of air necessary to move the combustion zone is directly proportional to the amount of fuel in contact with said zone remaining to be burned. Thus, a rock containing a large amount of residual or bypassed oil after reverse combustion would require a correspondingly large amount of air, which in turn results in high temperatures. Accordingly, reservoirs which have previously been subjected to a reverse combustion step and are still at about the temperature at which such reverse combustion occurred can require large quantities of air owing to high residual oil content and/or the pronounced coking tendency of the oil.

I have now discovered an improved method by which forward combustion can be carried out following a reverse burning operation through a carbonaceous deposit, particularly a reservoir containing primarily a tar or viscous oil. This method provides for a very substantial reduction in the quantity of air required to conduct the forward phase of the overall process. Since air injection costs ordinarily constitute a major item of expense in operations of this kind, it will be apparent that any appreciable reduction in the amount of air necessary for the job increases very substantially the economic incentive for recovering valuable gaseous and liquid products by means of underground combustion.

Briefly stated, the process of my invention is applicable where the combination of reverse burning followed by forward combustion is employed and is concerned with the injection of a suitable fluid into the reservoir following completion of the reverse combustion step and preceding the forward burning phase. For example, after reverse burning, I can inject into the heated reservoir water, a halogenated hydrocarbon such as, for example, carbon tetrachloride, chloroform, etc., a relatively volatile miscible fluid such as LPG, kerosene, low boiling fractions obtained from the liquid products recovered during the reverse burning step or the equivalent of such fractions, or an inert gas such as recirculated vent gas from the producing well.

Thus, the improved permeability occurring in a reservoir after the reverse burning step makes water a good material for use in accordance with my invention. With the reservoir already at a temperature of 400° to 500° F. after reverse combustion, water, when introduced through the injection well, is converted to steam thereby serving as a very effective driving force for moving the desired products ahead of the forward combustion front and toward the production well. This not only results

in markedly reducing the amount of air necessary to move products toward the production well but likewise brings about substantial savings in heat by transference of the heat from a hot portion of the reservoir to areas ahead of the combustion front containing oil or other desired products bypassed during the reverse burning step. This steam drive helps to push the oil out of the reservoir rock, leaving less oil to be burned during forward combustion which in turn results in decreasing the amount of air necessary for carrying out the forward combustion phase. This has the further advantage of increasing the rate at which the combustion front travels toward the production wells. As long as fuel remains in a given location in the reservoir, the front likewise stays in that location. By decreasing the quantity of fuel to be contacted by the combustion front, the latter will, therefore, move toward the output wells faster and the products will be produced at a faster rate. While the presence of some liquid water in the reservoir during forward combustion is a possibility under the conditions of my invention, it is a remote one. For example, at a reservoir temperature of about 500° F., pressures of the order of about 700 p.s.i. would be required in order for liquid water to be present.

If desired, water can be injected along with the air subsequent to the reverse burning step. In such case, the water flashes into steam which, in turn, travels toward and eventually passes through the combustion zone. This steam, as in the case described above, similarly forces residual or bypassed oil ahead of it and toward the producing wells. Alternatively, after the reverse burning step, water can be periodically injected in slugs followed in each instance by injection of air in quantities sufficient to maintain the combustion front.

As another variation, a miscible fluid, such as LPG, can be injected in place of water. The procedure when employing such a fluid can be essentially the same as used in the case of water except, of course, that injection of mixtures of air and LPG into the hot reservoir is to be avoided. Preferably, when a miscible fluid such as LPG is used, the injection well, after introduction of said fluid, should be purged with steam or other inert gas, such as vent gas, after which air can be injected into the reservoir. Of course, at the prevailing temperatures, e.g., 500° to 800° F., some of the injected LPG is burned on contact with the air. However, LPG being highly volatile is vaporized and travels through the reservoir rock forcing residual and bypassed oil toward the producing wells in much the same manner as is done in the case of steam. Also, as with steam (water), LPG could be injected periodically in the form of a slug followed in each instance by injection of air.

The reduction in size of the solvent (LPG or equivalent) bank owing to combustion of a portion of the bank can be avoided by substituting for LPG a noncombustible solvent for hydrocarbons such as halogenated hydrocarbon, for example, chloroform, trichloroethylene, carbon tetrachloride, etc. In this way the size of the solvent bank can remain substantially constant thereby permitting maximum recovery of bypassed or residual oil ahead of the forward combustion burning zone. Alternatively, these solvents may be employed in the form of mixtures thereof, including mixtures consisting only of noncombustible solvents as well as mixtures containing both combustible and noncombustible solvents. Also, with such noncombustible solvents, it is possible to inject them along with the air used in the combustion process instead of being restricted to the introduction of a separate slug or slugs of solvent as is required in the case of LPG or equivalent solvents.

This procedure of using LPG or a similar fluid subsequent to a reverse combustion step to assist in forward combustion would not be possible in an ordinary forward combustion process because displacement of the reservoir oil by said fluid is so efficient that no fuel re-

mains behind to be burned. Hence, combustion could not be maintained. In a reservoir preheated by reverse combustion as contemplated herein, ignition occurs wherever hot oil and air come in contact with one another.

Still another alternative is to replace the water or LPG injection step with the injection of a cool compressed inert gas. When the gas contacts the hot reservoir, it will expand, thereby aiding in moving the oil or other products toward the producing wells. This action, of course, is further assisted by the heat from the combustion zone itself on resumption of air injection. If desired, both air and inert gas can be injected simultaneously.

The amount of fluid injected in accordance with my invention may vary rather widely and depends on a number of variables such as, for example, the porosity of the formation and spacing of the wells. Generally speaking, however, the quantity of fluid thus injected may range from about 1 to 10 percent of the reservoir pore space to about 10 pore volumes.

The reverse combustion phase of my invention may be effected in a variety of ways already known to the art. While it generally may be desired to carry out the reverse burning step at as high a temperature as possible, there are instances where undesirable side effects, resulting from excessive temperatures can be harmful. For example, the composition of certain carbonaceous deposits is such that relatively high percentages of corrosive oxidation products, viz., organic acids, are produced when reverse combustion is effected at high temperatures causing extensive damage to the casing and production well tubing as well as other metal parts with which such products come in contact. Also, certain circumstances can arise under which it may be desirable only to reduce the viscosity of a tarry or low gravity oil deposit in order to condition the reservoir so that said deposit can be produced by other methods such as, for example, by gravity drainage or by waterflooding.

Accordingly, where relatively low temperatures are desired, i.e., temperatures not in excess of about 900° F., I have found that I am able to accomplish this object by operating at elevated reservoir pressures, at high oxygen concentrations, or at low air injection rates. Thus, where the air injection rate is substantially constant, I may employ reservoir pressures in an unfractured reservoir ranging upward from about 100 p.s.i. From the information I have obtained, it appears that the temperature in an unfractured reservoir decreases with increasing pressures for the reason that the rate at which oxygen reacts with the tar or oil is increased. This means, therefore, that such reaction can be made to proceed at a temperature lower than that required at lower reservoir pressures. Accordingly, pressures of from about 100 to about 250 p.s.i. should be employed before the effect on temperature is appreciable. The effect of pressure on temperature, however, tends to be less pronounced at pressures above about 500 p.s.i. The maximum pressure employed should be less than that which would cause fracturing of the reservoir rock or uncontrolled bypassing of gas therethrough.

Air injection rates likewise may vary widely depending partly, at least, on the porosity of the formation and the pressure employed. Thus, at substantially atmospheric pressure air injection rates of from about 2 to about 100 s.c.f./hr./ft.² may be used with rates of from about 50 to 75 s.c.f./hr./ft.² being preferred. In the case of high pressures, i.e., 100 to 500 p.s.i., rates of about 5 to 200 or 300 s.c.f./hr./ft.² may be employed with rates of 75 to about 125 s.c.f./hr./ft.² generally being in the preferred range. Lower injection rates are required to produce a given temperature at a lower pressure than are necessary to produce the same temperature at a higher pressure.

Oxygen concentrations required to produce reservoir temperatures not substantially in excess of 900° F. vary with the pressure and with the air flux. At high pressures and air fluxes, i.e., 250 p.s.i. and 100 s.c.f./hr./ft.², re-

spectively, oxygen concentrations of from about 20 to about 100 percent may be used. At minimum pressures utilized in my process, oxygen concentrations of from about 5 to about 100 percent may be employed. At a given pressure and oxygen injection rate, however, the temperature of the burning zone will be found to vary inversely with the oxygen concentration of the gas supplied to said zone. Thus, when the temperature is not as high as may be desired for optimum results, using air as the oxygen source, in a reverse combustion operation, an increase in combustion zone temperature can be produced by lowering the oxygen concentration of the stream going to said zone while maintaining the oxygen injection rate constant. This can be readily accomplished merely by diluting the air stream with nitrogen, a substantially inert flue gas or the equivalent thereof. Generally speaking, reservoirs will not be encountered that can tolerate less than about 5 to 10 percent oxygen in the gas to the combustion zone and still maintain satisfactory combustion conditions.

The process of my invention may be further illustrated by the conditions shown in the following specific example:

Example

The apparatus used in carrying out this work consists of three concentric tubes six feet long. The innermost tube, which is $\frac{3}{4}$ inches I.D. is constructed of 16 gauge Inconel. The intermediate or second tube is $\frac{5}{8}$ inches I.D. and is made of 16 gauge stainless steel. The outer tube is likewise 16 gauge stainless steel and is $1\frac{3}{4}$ inches I.D. The innermost tube is packed its full length with Athabasca tar sand. The space between this tube and the intermediate stainless steel tube is filled with diatomaceous earth as insulating material. The annulus formed by the outermost tube and the intermediate tube is packed with 20 to 40 mesh Ottawa flint shot sand. The entire combustion unit is covered with a one-inch thick layer of 85 percent magnesia insulation. Thermocouples are spaced along the length of the tube containing the tar sand and the tube containing the Ottawa flint shot sand. For each thermocouple extending into the tar sand, there are placed in the Ottawa sand two thermocouples at the same level but at points diametrically opposite the location of the particular tar sand thermocouple. The purpose of the addition thermocouples is to determine to what extent the outside combustion zone varied from a horizontal plane as it advances through the cell.

The combustion unit is suspended vertically with the outlet end at the bottom. Short sections of stainless steel tubing are connected to the outlets for both cells, i.e. the tar and Ottawa flint shot sand cells. Air, propane, and oxygen are then injected simultaneously but independently into each of the aforesaid cells through appropriate inlet piping at controlled rates. The resulting mixtures in each of the cells, upon reaching the outlets at the bottom thereof, are ignited. The oxygen concentration is increased and the air rate decreased until the flame flashes back through the outlet tubes into the cells. The oxygen rate is gradually decreased until both cells are burning on air and propane. When the thermocouple indicates the combustion zone has moved into the tar sand, the outlet piping for handling combustion products is connected to the base of the unit and propane injection is stopped to the cell containing the tar sand. Simultaneously, carbon disulfide is substituted for propane in the outer cell since the former burns at a temperature close to that which it is desired to maintain in the tar cell.

The air rate to the innermost cell is maintained constant during the course of reverse combustion. The air and carbon disulfide rates to the outer cell are periodically adjusted to maintain the combustion zone in the outside cell slightly ahead of the combustion zone in the tar sand. When the combustion zone in the outside cell approaches the inlet tubes, carbon disulfide injection is discontinued. When the combustion zone in the tar sand reaches the

inlet or air injection line, combustion in a reverse direction ends owing to a lack of fuel at that point. Prior to beginning forward combustion in Runs 7, 8 and 9 a fluid is injected into the hot tar sand in the quantity indicated in the table below. Thereafter, injection of air to the cell is resumed causing forward combustion to proceed therethrough. The air rate to the tar sand during the forward combustion phase is arbitrarily increased until the combustion zone temperature reaches approximately 1000 to 1500° F. This is about the highest temperature level that can be maintained without damage to the apparatus.

Forward combustion is continued until the sand is burned completely clean. The cell which originally contained the Athabasca tar sand is then removed and weighed to determine the amount of tar and water removed. One end of the cell is opened and the sand removed.

Nine separate runs are carried out in the manner described above, using different air injection rates while the tar sand cell outlet is held at the pressures indicated. The conditions employed and the results obtained are shown in the table appearing below:

TABLE

Run No.	1	2	3	4	5	6	7	8	9
Reverse Combustion Stage:									
Air Injection Rate, s.c.f./hr./ft. ²	7.5	51	150	310	11	50	50	50	110
Outlet Pressure, p.s.i.g.	0	0	0	0	250	250	500	250	250
Percent O ₂ in Injected Gas	21	21	21	21	21	21	21	21	10
Combustion Zone Temperature, ° F.	494	800	1,112	1,400+	378	575	540	570	520
Combustion Zone Velocity, ft./hr.	0.066	0.12	0.20	0.18	0.11	0.25	0.28	0.26	0.051
Oil Recovery Efficiency, Wt. Percent	29.8	41.0	37.4	5.5	Trace	11.6	10.9	11.9	10.3
Gas-Oil Ratio, M s.c.f./bbl.	7.05	18.2	37.4	580	-----	33	37.8	37.4	39.2
Water-Oil Ratio, Volume/Volume	1.14	0.7	1.1	8.5	-----	2.2	2.1	2.2	2.1
Heat Loss, Percent	-78	21	24	65	0	-22	4	7	11
Intermediate Treatment:									
Fluid Injected	(²)	(²)	(²)	(²)	(²)	(²)	(²)	(⁴)	(⁵)
Volume Injected, Percent of Total							20	10	5
Reservoir Pore Volume									
Subsequent Forward Combustion Stage:									
Combustion Zone Temperature, ° F.	1,310	1,970	2,190	(⁶)	1,920	1,850	1,270	980	940
Oil Recovery Efficiency, Wt. Percent	14.0	8.3	1.0	0	61.0	44.4	57.6	67.4	69.9
Gas-Oil Ratio, M s.c.f./bbl.	30.8	97	320	-----	26.2	41	9.2	8.6	7.9
Combined Operation:									
Overall Oil Recovery Efficiency, Wt. Percent	43.8	49.3	38.4	5.5	61.0	56.0	68.5	79.3	80.2
Overall Gas-Oil Ratio, M s.c.f./bbl.	25.2	39	81	-----	27.3	39.6	23.2	21.2	26.1

¹ Nitrogen also injected.

² None.

³ Water.

⁴ Kerosene.

⁵ Carbon Tetrachloride.

⁶ Combustion stopped.

From an inspection of the above table, it will be apparent that a number of advantages are to be gained by operating in accordance with the present invention. Thus, in comparing Runs 5 and 9, it is seen that when the concentration of oxygen fed to the burning zone is reduced as in Run 9, the temperature increases and the amount of oil recovered increases. The only substantial difference in conditions used in the two runs was in the composition of the oxygen-containing gas going to the burning zone, the oxygen feed rate being the same in both cases. On the other hand, increasing the oxygen concentration of the gas used, for example, to a figure of 30 to 40 percent, can result in greatly reduced combustion zone temperatures, provided other operating conditions are held substantially constant. In some instances temperatures of about 575° F. are reached when using ordinary air during reverse combustion. However, if the oxygen content of the injected gas is increased, e.g., to a concentration of 25 to 30 percent and conditions are allowed to otherwise remain the same, a reduction in temperature of from 75° to 100° F. is realized. Also, the

effect of pressure is demonstrated in Runs 2 and 6. Thus, in Run 2, no additional pressure was applied to the system and the temperature of the reservoir was 800° F., resulting in an oil recovery of 41 percent. In Run 6, an additional pressure of 250 p.s.i. was used, resulting in a temperature of 575° F. and an oil recovery of 11.6 percent. While the oil recovery in Run 6 was lower than that obtained in Run 2 during the reverse combustion step, the overall recovery in Run 6 was 56 percent, as compared to 49.3 percent in Run 2. Since the other conditions in Runs 2 and 6 were essentially the same, it is reasonable to conclude increased pressure was responsible for the improved recovery. Another advantage of using high pressure during the reverse combustion step is that oftentimes when combustion is initiated at the face of the producing well, the temperature can be sufficiently high that all of the carbonaceous material in the vicinity of the well bore is burned. In unconsolidated formations, such as the McMurray formation, in which Athabasca tar is found, sand flows into the well bore if all of the tar is burned off. Hence, in starting up a reverse combustion operation in such a formation, the use of pressure is desirable at least during the initial stages in order to

hold the temperature to a suitably low level, e.g., 400°–500° F. After the burning zone has moved away from the production well bore a distance of two or three feet, the pressure can be decreased thereby permitting higher combustion temperatures, e.g., 800°–900° F. With further regard to the undesirability of high temperatures in the vicinity of the well bore, it is to be pointed out that even if the oil or tar is not in an unconsolidated formation, high temperatures cannot only cause the rock to spall off into the well bore, but extensive damage can be done to the casing and tubing.

The advantage of injecting a fluid into a hot formation just prior to forward combustion, in accordance with my invention, is very clearly demonstrated by comparing the results obtained in Runs 7, 8 and 9 with those secured in the other runs. The desirability of injecting a fluid between the reverse and forward combustion steps is not only expressed in terms of higher oil recoveries, but is also shown in the maximum temperature reached during the forward burning phase of Runs 7, 8 and 9. These relatively lower temperatures result from the fact that

the steam, kerosene and carbon tetrachloride, as used, cause the residual oil to flow out from the previously bypassed areas ahead of the burning front. This additional oil is removed either by the action of high pressure gases resulting from partial or complete vaporization of the injected liquid or from the solvent action of the injected liquid on the residual oil. Such action by the injection of liquid in accordance with the present invention, of course, leaves less oil to be burned which, in turn, permits the front to move forward at a faster rate giving up less heat to the reservoir rock.

It will further be seen from Runs 7, 8 and 9 that the air rates per barrel of oil recovered are very substantially lower than those required for even lower oil recoveries obtained in the other runs where the operating conditions were essentially the same as those used in Runs 7, 8 and 9, except for the injection of a fluid after reverse combustion as called for by the present invention.

Although the process of my invention, as applied to the recovery of oil, has been described largely with respect to petroleum tars and low gravity oils, it is likewise applicable to higher gravity crudes. Thus, my invention may be used to recover oil from reservoirs which have already been subjected to primary and/or secondary recovery methods. Also, it may be applied to reservoirs containing high gravity oil but low reservoir energy, e.g., very little, if any, dissolved gas.

While I have mentioned only the use of air as an oxygen source in carrying out my process, oxygen-enriched air, of course, may be employed. Also, it may be desirable to recycle a portion of the combustion products from the producing well, particularly carbon dioxide, and mixing said products with the air injection stream. It is to be further pointed out that the process of my invention is subject to numerous modifications without departing from the scope thereof. For example, after the reverse combustion step has been completed, the fluid may be injected into the formation via a well that was a producing well during reverse burning. Under such conditions, of course, the subsequent forward combustion phase is carried out by injecting air into said former producing well and using the former injection well as a producing well. In connection with this latter step, it will be appreciated, of course, that if the formation face in the former producing well has cooled off appreciably, it will be necessary to ignite said face or otherwise elevate the temperature thereof to a level such that the combustion zone will be formed on subsequent air injection for the aforesaid formed combustion phase.

It will be apparent from the above description that a wide variety of fluids—either in the liquid or gaseous state when injected into the formation—can be used in carrying out the process of my invention. Accordingly, the term "fluid" as used in the present claims is intended to be directed to such liquids or gases, other than air, that are not corrosive under the conditions of use and/or do not react with a component or components in the carbonaceous deposit to form a product or products that interfere with the recovery of the hydrocarbons or other desired products from said deposit.

I claim:

1. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposits an oxygen-containing gas, initiating a zone of combustion in said deposit at a point adjoining said producing well, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection well, thereafter injecting a fluid of the type defined into one

of said wells, said fluid being injected in an amount insufficient to interfere with the temperature prevailing in the burned area between said wells, next introducing an oxygen-containing gas into said deposit through one of said wells, while the face of said deposit at said one of said wells is substantially at combustion temperature, continuing the introduction of said gas, and recovering the resulting valuable products from the other of said wells.

2. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point intermediate said injection and producing wells, subjecting said deposit to a pressure of at least about 100 p.s.i., but less than that required to cause fracturing of said deposit, thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection well, said pressure being applied until said zone has reached the area adjacent said injection well whereby the temperature of said zone is held below that required to crack the carbonaceous material in said deposit, thereafter injecting a fluid of the type defined into said injection well and into said deposit in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, next introducing an oxygen-containing gas into said deposit through said injection well whereby the course of said zone is reversed and travels concurrently with said gas toward said producing well and recovering the resulting valuable products from said producing well.

3. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point adjoining said producing well, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent the injection well, reducing the pressure on said deposit, thereafter injecting a fluid of the type defined into said production well in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, subsequently further introducing oxygen-containing gas into said deposit through the original producing well whereby a combustion zone is maintained and propagated concurrently with said gas toward the original injection well, and recovering fluids resulting therefrom through said original injection well.

4. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point adjoining said producing well, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection well, thereafter injecting water into one of said wells and into said deposit in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, subsequently further introducing oxygen-containing gas into said deposit through said one of

said wells so as to propagate said zone through said deposit in the same direction as the flow of said gas therethrough, continuing the introduction of said gas, and recovering the resulting valuable products from the producing well.

5. In a process for the underground combustion of a petroleum deposit, said deposit being penetrated at specified points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point adjoining said producing well, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection well, thereafter injecting a solvent for said deposit into one of said wells and into said deposit in an amount corresponding to from 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, subsequently further introducing oxygen-containing gas into said deposit through said one of said wells so as to propagate said zone through said deposit in the same direction as the flow of said gas therethrough, continuing the introduction of said gas, and recovering the resulting valuable products from the producing well.

6. The process of claim 5 in which the solvent employed is a noncombustible solvent.

7. The process of claim 6 in which the noncombustible solvent is a chloriated hydrocarbon.

8. The process of claim 6 in which the chlorinated hydrocarbon is carbon tetrachloride.

9. The process of claim 5 in which the solvent is kerosene.

10. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by two wells, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point adjoining one of said wells, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying oxygen-containing gas through the other of said wells to said zone to maintain said zone and propagate it through said deposit toward said other of said wells until said zone has reached an area adjacent said other of said wells, controlling the temperature of said zone by varying the oxygen content of said gas indirectly with the intensity of the temperature desired in said zone, thereafter injecting a fluid of the type defined into one of said wells in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, subsequently introducing an oxygen-containing gas into said deposit through the last-mentioned well while the face of said deposit at said last-mentioned well is substantially at combustion temperature, continuing the introduction of said gas so as to propagate a combustion front toward the other of said wells, and recovering the resulting valuable products from the last-mentioned well.

11. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point intermediate said injection and producing wells, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection

well, thereafter injecting a mixture of oxygen-containing gas and a non-combustible solvent for said deposit into said deposit through said injection well, whereby the course of said zone is reversed and travels concurrently with said gas toward said producing well, said solvent being employed in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, and recovering the resulting valuable products from said producing well.

12. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion therein at a point adjoining said producing well, holding the temperature in the area of said producing well to a maximum of not more than about 500° F. by subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit while supplying an oxygen-containing gas to said zone through said injection well to maintain said zone and to propagate it a distance of not more than about 3 to 4 feet from said point, thereafter reducing the pressure on said deposit to increase the temperature of said zone while injecting said gas through said injection well, continuing injection of said oxygen-containing gas through said injection well until said zone has reached an area adjacent said injection well, thereafter injecting a fluid of the type defined into one of said wells, and into said deposit in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, next introducing an oxygen-containing gas into said deposit through said one of said wells whereby said zone is maintained and propagated toward the other of said wells, and recovering the resulting valuable products from said other of said wells.

13. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point intermediate said injection and producing wells, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection well, thereafter injecting a mixture of oxygen-containing gas and water into said deposit through said injection well, whereby the course of said zone is reversed and travels concurrently with said gas toward said producing well, said water being employed in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, and recovering the resulting valuable products from said producing well.

14. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said deposit at a point intermediate said injection and producing wells, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection well, thereafter injecting alternate slugs of an oxygen-containing gas and a fluid into said deposit through said injection well, whereby the course of said zone is reversed and travels concurrently with said gas

13

toward said producing well, said fluid being employed in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, and recovering the resulting valuable products from said producing well.

15. In a process for the underground combustion of a carbonaceous deposit, said deposit being penetrated at spaced points by an injection well and a producing well, the improvement which comprises injecting into said deposit an oxygen-containing gas, initiating a zone of combustion in said producing well, subjecting said deposit to a pressure of from about 100 p.s.i. to a pressure just below that required to fracture said deposit, thereafter supplying an oxygen-containing gas through said injection well to said zone to maintain said zone and to propagate it through said deposit toward said injection well until said zone has reached an area adjacent said injection well, thereafter injecting alternate slugs of an oxygen-containing gas and water into said deposit through said injection well, whereby the course of

14

said zone is reversed and travels concurrently with said gas toward said producing well, said water being employed in an amount corresponding to from about 1 to 10 percent of the pore space in said deposit to about 10 pore volumes, and recovering the resulting valuable products from said producing well.

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