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C. CONNALLY, JR

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EMPLOYING A HEATED PERMEABLE CHANNEL AND
FORWARD IN SITU COMBUSTION IN
SUBTERRANEAN FORMATIONS

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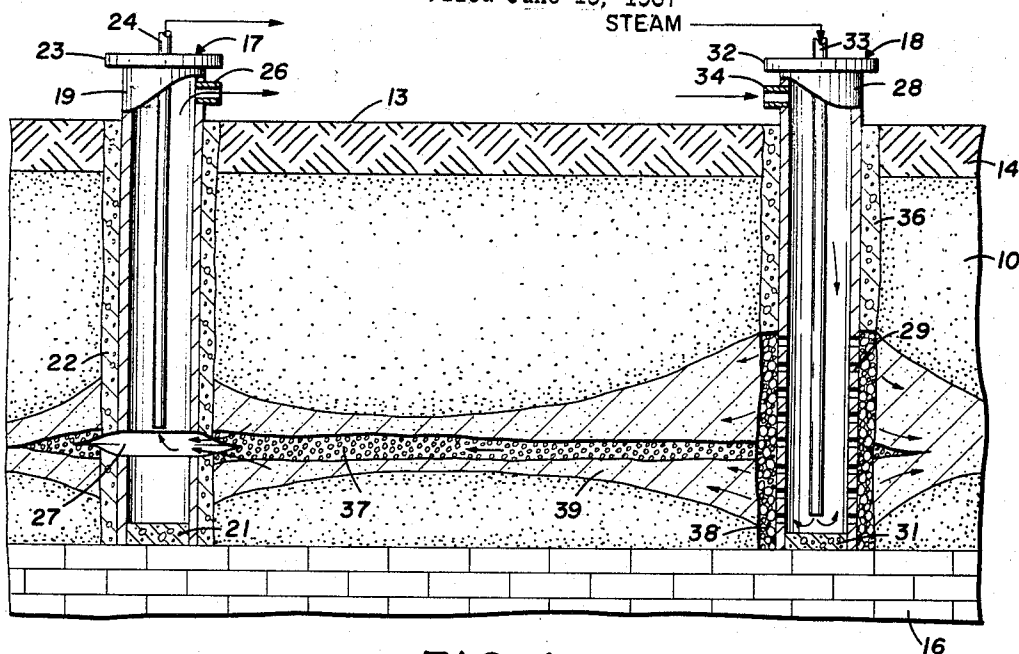


FIG. 1

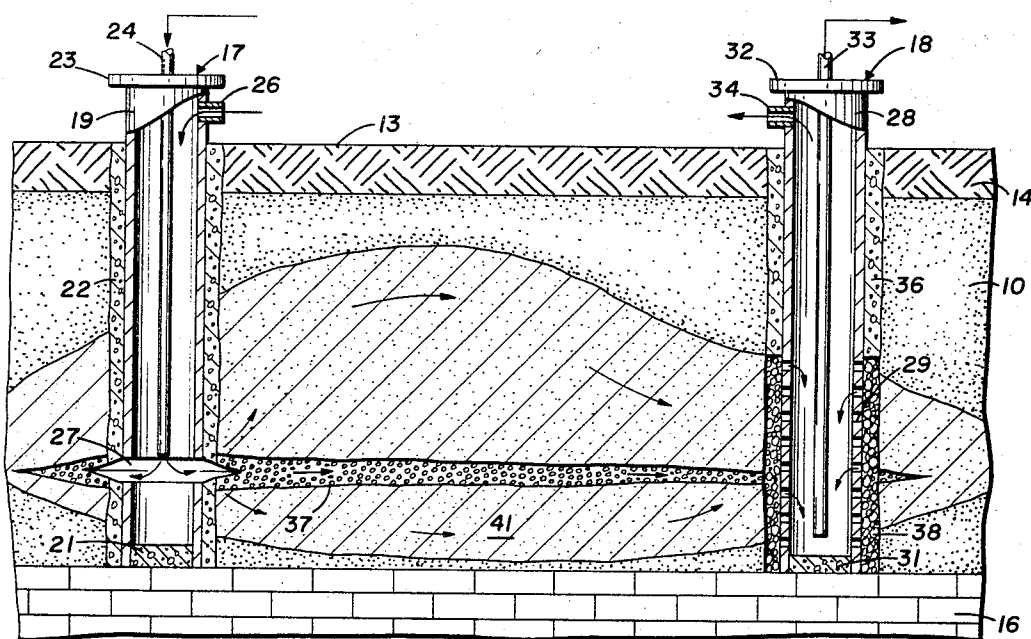


FIG. 2

INVENTOR

CARL CONNALLY, JR.

Emil J. Bednar

ATTORNEY

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THERMAL RECOVERY METHOD FOR HEAVY HYDROCARBONS EMPLOYING A HEATED PERMEABLE CHANNEL AND FORWARD IN SITU COMBUSTION IN SUBTERRANEAN FORMATIONS

Carl Connally, Jr., Dallas, Tex., assignor to Mobil Oil Corporation, a corporation of New York
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ABSTRACT OF THE DISCLOSURE

A method using forward in situ combustion for the recovery of heavy, viscous-nonflowing hydrocarbons from subterranean formations. Initially, a permeable flow channel, e.g., a propped fracture, is formed between spaced-apart first and second wells. Bidirectional steam flows from the wells heat the flow channel. An oxidizing material, or combustion-supporting gas, is passed from the first well through the flow channel to the second well to effect a forward in situ combustion front. This front moves toward the second well and displaces formation fluid via the flow channel into the second well from which it is produced. Hydrocarbons are then recovered from the produced formation fluid. If desired, certain steps may be practiced: to secure maximum production of recoverable hydrocarbons from a minimum flow of the combustion-supporting gas, to control the temperature created in the second well means for optimum hydrocarbon recovery, to inject water with the combustion-supporting gas to control heat flow from the combustion front, and to periodically interrupt fluid production from the second well to reduce the elevated temperatures which exist in the well.

Background of the Invention

(1) *Field of the invention.*—This invention relates to the recovery of heavy, viscous-nonflowing hydrocarbons from subterranean formations. More particularly, it relates to a thermal method for producing hydrocarbons in recoverable amounts from earthen formations by a combination of steam injection, and forward in situ combustion steps practiced within a highly permeable flow channel.

(2) *Description of the prior art.*—Within subterranean formations reside vast quantities of hydrocarbons not recoverable by conventional oil production techniques. Conventional oil production techniques are rendered ineffective by the high viscosity, or high pour point, of the hydrocarbons at the existing formation conditions which make these hydrocarbons substantially immobile.

Various techniques have been proposed for heating the formations to reduce the viscosity of the hydrocarbons so they become mobile and thereby can flow into a production well. Such techniques include forward and reverse in situ combustion procedures, heated fluid injections, and injections of viscosity-thinning solvents such as diesel oil. Of these techniques, forward in situ combustion appears more suitable.

In forward in situ combustion, carbonaceous material in the formation is ignited in the presence of an oxygen-containing gas, usually the air, for providing the combustion front. Then, the oxygen-containing gas is caused to flow in the same direction as the combustion front is to be moved. In certain instances, forward in situ combustion may be difficult to control for the recovery of hydrocarbons of great viscosity from subsurface formations, particularly where the initial temperature of these formations is rather low. For example, the heavy oil sands

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of California and the tar sands of the Athabasca River deposits in Canada are of this nature. Forward in situ combustion, in such deposits, under certain operating conditions causes a liquid bank of formation fluid to be created immediately ahead of the combustion front. This liquid bank is principally formed of the highly viscous hydrocarbons which cannot flow to an adjacent production well. The liquid bank also can terminate the flow of the oxygen-containing gas which maintains the combustion front. As a result, the combustion front can be extinguished. If the liquid bank occurrence in these formations could be avoided, forward in situ combustion would be a most desirable method for the production and recovery of heavy hydrocarbons. The present invention is directed toward a procedure wherein the method of forward in situ combustion can be employed for the production and recovery of heavy viscous hydrocarbons from subterranean formations without the liquid bank problem.

Summary of the invention

The present invention is a method for the recovery of viscous-nonflowing hydrocarbons from a subterranean formation. A first well means is formed into the formation and arranged for fluid flow to only a lower portion of the formation at a restricted horizon. Spaced apart from the first well means is a second well means formed in the formation. The second well means is arranged for fluid flows to the lower 30 to 60 percent of the vertical extent of said formation. Thereafter, a horizontally oriented, highly permeable, flow channel is formed through the lower portion of the formation to extend from the first well means at the restricted horizon to the second well means. Steam is passed from the first well means through the flow channel into the second well means so that the temperature of fluids entering the second well is increased to a minimum of about 200° F. Then, steam is passed from the second well means through the flow channel to flow into the first well means. Formation fluid is produced from the first well means at a rate not substantially less than the rate at which fluid is being produced into such well means so as to maintain a minimum back pressure in this well means. Next, a combustion-supporting gas is passed from the first well means through the flow channel to the second well means. The combustion-supporting gas is employed in an amount sufficient to flow into the second well means and to displace formation fluid from the flow channel thereby to maintain its high permeability to fluid flow. The combination-supporting gas flow and the elevated temperature of the formation adjacent the first well means will normally result in spontaneous ignition of the carbonaceous matter for creating a forward in situ combustion front. Conventional ignition procedures, such as by use of an electrical ignitor, may be employed in cases where spontaneous ignition is not achieved. The flow of combustion-supporting gas is adjusted while moving the combustion front toward the second well means to maintain a continuous flow of said gas, combustion products thereof, and the displaced formation fluid into the second well means, at a temperature between about 200° F. and the elevated temperature where combustion of produced formation fluid occurs in the second well means. Lastly, the formation fluid is produced from the second well means, and hydrocarbons are recovered from such fluid. If desired, the amount of hydrocarbons recovered from the formation fluid may be correlated to the flow of combustion-supporting gas in a certain manner so that a maximum production of recoverable hydrocarbons is obtained from a minimum flow of combustion-supporting gas. In another aspect, the temperature within the second well means may be adjusted to improve the recovery

of hydrocarbons by temperature maintenance in the second well means between the steam-water equilibrium temperature and the temperature where significant combustion of produced formation fluid occurs. Water may be injected into the first well means along with combustion-supporting gas so as to move the combustion front toward the second well means with just the added amounts of water sufficient to maintain a flow of steam and produced formation fluid into the second well means. When the temperature within the second well means begins to rise due to the approach of the combustion front, the well means may be periodically shut in until it cools and then opened to the production of formation fluid until the temperature rises to indicate the combustion of formation fluid is again to occur.

Description of the drawings

In the drawings, FIGURES 1 and 2 are vertical sections taken through the same portion of a subterranean formation containing heavy hydrocarbons during the practice of initial and terminal steps in the method of the present invention. Additionally, the formation is provided with suitable structures for carrying out the various steps of the present method. In the drawings, the same numeral reference and nomenclature are used for the same structure.

Description of specific embodiments

Referring now to FIGURES 1 and 2 of the drawings, there is shown a subterranean formation 10 which resides below the earth's surface 13 beneath an overburden 14 and superimposed above a substrata 16. The overburden 14 and substrata 16, for purposes of this description, may be considered to be free of recoverable hydrocarbons. The formation 10 is a reservoir for formation fluid which contains heavy, viscous-nonflowing hydrocarbons, of any origin. For example, the formation 10 may be a sand strata containing heavy hydrocarbons. Particularly, the formation 10 can be the oil sands found in the North American continent. These sands include the heavy oil sands of California and the tar sands of Canada. The formation fluid present in the formation 10 may include, besides the hydrocarbons, connate water and slight amounts of gases. However, the nature of the formation 10 is such that the heavy hydrocarbons cannot be recovered by conventional oil production techniques. In this regard, the hydrocarbons are considered practically non-flowing and immobile under formation conditions.

As one step in the present method, spaced first and second well means are provided, by any suitable procedure and apparatus, into the earth to extend from the earth's surface 13 into the formation 10. These well means are arranged for fluid communication between the earth's surface 13 and the formation 10 and can be in the form of wells 17 and 18. The well 17 is arranged to permit fluid flows to the lower portion of the formation 10 at a restricted horizon. The well 18 is arranged to provide fluid flows to the lower 30 to 60 percent of the vertical extent of the formation 10.

The well 17 has a casing 19 extending from the earth's surface 13 downwardly to the lower extremities of the formation 10. The casing 19 is sealed, adjacent the substrata 16, by a cement plug 21. A cement sheath 22 secures the casing 19 to the traversed earthen strata. A wellhead 23 encloses the upper end of the casing 19. A tubing 24, for carrying fluids, extends through the wellhead 23 to the lower portions of the well 17. A second fluid entry into the well 17 is provided by port 26.

The well 17 is provided a fluid entry to the lower portion of the formation 10. For this purpose, V-shaped notch 27 is cut horizontally through the casing 19 and cement sheath 22 in the lower portion of the formation 10. Thus, fluid can flow between the well 17 and only the lower portion of the formation 10 at a restricted horizon.

The well 18 is extended through the formation 10 to

about the same total depth as the well 17. The well 18 has a casing 28 extending from the earth's surface 13 to the lowermost portions of the formation 10. The lower portion of the casing 28 is provided with openings 29 to permit fluid flows between the well 18 and the lower 30 to 60 percent of the vertical extent of the formation 10. The casing 28 is sealed with a suitable cement plug 31 adjacent the substrata 16. A wellhead 32 encloses the upper extremity of the casing 28. A tubing 33 for carrying fluids extends through the wellhead 32 into the lower portions of the well 18. An additional fluid entry into the well 18 is provided by port 34. By this means, fluid flows are permitted between the lower 30 to 60 percent of the vertical extent of the formation 10 and the well 18. A cement sheath 36 about the uppermost portions of the well 18 secures it to the adjacent earthen strata.

As another step, a horizontally oriented, highly permeable flow channel 37 is formed through the lower portion of the formation 10. The flow channel 37 is formed in any suitable manner to provide a path by which fluids can flow through the formation 10 at greatly reduced pressure gradients. The flow channel 37 extends from the well 17 at the horizon of the notch 27, across the formation 10 to the well 18. The flow channel 37 provides fluid communications through the formation 10 between the wells 17 and 18.

Preferably, the flow channel 37 is a prop-filled fracture. For this purpose, a pressurized fracturing fluid is introduced to the formation 10 through the well 17. Usually the fracturing fluid is introduced through the tubing 24 of the well 17 with the port 26 closed. The fracturing fluid is applied with sufficient pressure to the formation 10 at the notch 27 until a horizontal fracture is formed and extended to the well 18. A prop such as sand, glass or metal beads, or other suitable propping material, is forced into the fracture to prevent its subsequent closure by formation pressure.

It is preferred that the flow channel 37 be formed by fracturing and propping with a suitable propping material. However, other constructions of the flow channel 37 may be employed for obtaining good results. For example, the formation 10 is fractured between the wells 17 and 18. Then, steam is passed through the fracture to extract suitable amounts of formation fluid from the adjacent areas of the formation 10. Thus, a highly permeable channel is formed even though the fracture may be closed later by formation pressure. Alternatively, a flow of suitable solvent, such as LPG or gasoline, may be effected between the wells 17 and 18 through the desired horizon of the formation 10. The solvent flow extracts formation fluid from its flow path to form a highly permeable channel through the formation 10.

After establishment of the flow channel 37, the wells 17 and 18 are prepared for the injection of steam into the formation 10. For this purpose, these wells are usually cleaned of residual fracturing material and proppant material. At this time, it may be desired to provide a gravel pack 38, by conventional procedures, around the lower portion of the well 18. Although the gravel pack 38 is not a necessity for the practice of the present method, it is of considerable advantage in holding back sand, or other material, of the formation 10 which tends to enter the well 18 along with formation fluid.

With special attention given to FIGURE 1, the steps of steam injection will be described. Steam, of any quality and supplied from any suitable source, is applied to the well 17 for injection into the flow channel 37. Preferably, steam is introduced through the tubing 24 with the port 26 closed. The steam is passed into the flow channel 37 until the flow channel is heated along its entire length to the well 18. At this time, the temperature of fluids entering the well 18 will be increased to about 200° F. The steam is injected in a sufficient amount until it flows through the flow channel 37 into the well 18. As one result, the elevated temperature for initiating combus-

tion, by spontaneous ignition upon introduction of oxidizing fluids, adjacent the well 17 in the formation 10 is obtained. As another result, the flow channel 37 provides a heated environment through which the heavy hydrocarbons of the formation fluid may readily flow without forming liquid blocks. Thus, liquid blockage problems in the flow channel 37 and formation 10 adjacent the well 17 are avoided.

Unless excessive amounts of steam are passed through the flow channel 37 to the well 18, the formation 10 immediately adjacent the well 18 and remote from the flow channel 37 may remain sufficiently cold that a liquid blockage problem can arise. The employment of steam in such amount to avoid this problem would be economically wasteful. By the following step of this method, such excessive amounts of steam are not required to be passed through the flow channel 37 from the well 17.

At this time, steam is injected through the well 18 to flow through the flow channel 37 into the well 17. The steam can be of the previously described character; and it may be introduced through the tubing 33 or the port 34 of the well 18. It is preferred to employ the tubing 33 for carrying steam into the lower portions of the well 18 to reduce heat losses therein. Steam is injected through the well 18 in a sufficient amount until it flows through the flow channel 37 into the well 17. The steam readily flows through earlier heated parts of the flow channel 37 adjacent the well 17. However, the steam penetrates a large vertical extent of the formation 10 and thereby heats a larger vertical and horizontal portion of the formation 10 adjacent the well 18 than about the well 17.

As a result of the preceding steps of flowing steam through the wells 17 and 18 into the flow channel 37, a heated area 39 is formed in the formation 10. The heated area 39 extends through the formation 10, at a lower horizon, between the wells 17 and 18. This heated area 39, of course, includes the flow channel 37. It will be apparent that fluids can flow through the flow channel 37 very readily without creating a liquid block.

During the time that steam is introduced through one of the wells 17 and 18, formation fluid, water, and steam will be produced into the other well. These fluids may be recovered from such wells. Particularly, the fluid produced into the well 17 is produced therefrom at a rate not substantially less than the rate at which fluid is being produced into the well 17. This fluid production maintains a minimum back pressure in the well 17 and insures that the steam passing through the flow channel 37 can elevate the temperature of the carbonaceous material residing in the vicinity of the well 17 to an extent that spontaneous ignition can be readily obtained upon introduction of an oxidizing fluid.

Referring now to FIGURE 2, as another step, a combustion-supporting gas is injected through the well 17 to flow through the flow channel 37 and openings 29 into the well 18. At this time, the formation 10 adjacent the flow channel 37 between the wells 17 and 18 is maintained at the ignition temperatures of the resident carbonaceous matter. Supplement heating may be used for this purpose where cooling of the formation 10 has inadvertently occurred, or for other reasons. The combustion-supporting gas is any oxidizing medium capable of sustaining combustion of carbonaceous material residing in the formation 10. The combustion-supporting gas usually is air. It may be admixed with additional oxidant, or inert material, for varying the concentration of the oxidizing material therein. The flow of the combustion-supporting gas ignites, in the vicinity of the well 17, the carbonaceous matter within the formation 10 which has been heated to temperatures necessary to promote rapid oxidation and achieve spontaneous ignition. As a result, a forward in situ combustion front is created in the flow channel 37 and the adjacent portions of the heated area 39. Continued injection of the combustion-supporting gas moves the in situ combustion front through the formation 10,

principally along the flow channel 37 and heated area 39, toward the well 18. This flow should be in an amount sufficient to displace formation fluid into the well 18 and to maintain the high permeability to fluids of the flow channel 37.

The combustion front movement produces large amounts of heat energy which are dissipated-in-part through the formation 10 by convection, conduction, and radiation. This heating effect, along with the products of combustion, produces a thinning of the heavy hydrocarbons in the formation fluid. The heat-thinning and other effects of the combustion front cause the formation fluid, and included hydrocarbons, to flow into the well 18. The many effects from in situ combustion front movement for producing hydrocarbons are well known, and therefore, need not be presently discussed in greater detail.

In another step, the combustion-supporting gas flow from the well 17 into the formation 10 is adjusted to a sufficient amount to maintain a continuous flow of the combustion-supporting gas, the combustion products from the combustion front, and displaced formation fluid, into the well 18. These fluids may be recovered through the tubing 33 and the port 34. Additionally, the flow of the combustion-supporting gas is adjusted to maintain the temperature of the fluids within the well 18 at a temperature of between about 200° F. and the elevated temperature where combustion of the produced formation fluid occurs. Suitable monitoring means may be employed for determining these temperature conditions. Such monitoring means are conventional and are not herein described. The flow of the combustion-supporting gas, to obtain this result, may be by varying its rate as long as all fluid flow does not cease into the well 18. Additionally, the concentration of oxidant within the combustion-supporting gas may be varied by addition of oxidant, or inert diluent. Generally, the oxidant in the combustion-supporting gas will require dilution to prevent excessive temperatures in the well 18. Such dilution may be effected by intermixing an inert material or combustible gas with the combustion-supporting gas. If desired, the recovered products of combustion from the well 18 may be recycled to provide the desired dilution of the combustion-supporting gas.

The step of adjusting the flow of combustion-supporting gas is greatly advantageous in that the conditions maintained within the well 18 provide the optimum environment for the production of formation fluid from the formation 1. It has been found that for all practical purposes, heavy hydrocarbons when heated to a temperature of above 200° F. are sufficiently thinned as to not create any production problems, or any liquid blockage problems within the formation 10. However, heating the hydrocarbons to elevated temperatures, where their combustion occurs within the well 18, is greatly undesired for several reasons. One reason is the thermal destruction of the metal conduits of the well 18. Another reason is combustion of the desired hydrocarbons reduces their recovery from the formation fluid. By practicing this step, these undesired results are avoided while securing a greatly advantageous increase in the production of hydrocarbons into the well 18. Also, with these controlled conditions of temperature within the well 18, the formation fluid cannot be displaced in the formation 10 toward the well 18 at a rate greater than fluid can be produced from the heated area 39 and flow channel 37 into the well 18.

Use of the flow channel 37, and practice of the step of adjusting the flow of combustion-supporting gas during movement of the forward in situ combustion front, provide an environment for obtaining great vertical sweep efficiency in the front. Particularly, the in situ combustion front, in moving toward the well 18, can expand vertically in the formation 10 at greatly increased rates to displace formation fluid primarily through the heated areas of the heated zone 39 and the flow channel 37 into the production well 18. This significant vertical expansion of the forward combustion front produces a swept area 41. The

swept area 41 increases vertically upwardly in a greater dimension than downwardly because of the several effects of gravity drainage and heat expansion in the formation 10.

If desired, the conditions surrounding the movement of the in situ combustion front may be varied to increase further the production, and recovery, of hydrocarbons from the formation 10.

More particularly, the formation fluid displaced into the well 18 can be recovered through the tubing 33. Hydrocarbons are recovered from this fluid by suitable apparatus, which may be of any construction. The amount of hydrocarbons recovered from the formation fluid is measured. This measurement is correlated to condition changes obtained by varying the flow of combustion-supporting gas as required to maintain a temperature within the well 18 (between the limits of about 200° F. and the elevated temperature where combustion of produced formation fluid occurs) until a maximum production of recoverable hydrocarbons is obtained for a minimum flow of the combustion-supporting gas. Additionally, at this condition, the greatest vertical sweep efficiency is obtained in the combustion front moving toward the well 18.

Preferably, in the step of maintaining the temperature between the stated limits in the well 18, the adjustment of the flow of combustion-supporting gas provides a temperature between the steam-water equilibrium temperature in the well 18 and the temperature where significant combustion of produced formation fluid occurs at the conditions existing within the well 18. It will be apparent that these conditions vary from specific minimum and maximum temperatures, as a result of changes in the composition of fluids entering the well 18, and also the downhole pressure conditions.

After the combustion front has moved from the well 17 a sufficient distance in the formation 10 to become established firmly, another step may be taken to improve the transfer efficiency of the heat produced by the combustion front. For example, this distance can be the movement of the front after having passed through one-tenth the pore volume of the formation 10 residing between the wells 17 and 18. It will be apparent that steam is formed and condensed in response to movement of the combustion front. For example, water is formed by chemical reactions occurring at the combustion front. This water is first generated as steam and later condenses downstream of the in situ combustion front. Additionally, connate water in the formation 10 is transformed to steam and it likewise condenses at a point downstream of the combustion front. In the present step, water is injected with the combustion-supporting gas from the well 17 into the formation 10 to pass through the combustion front. The amount of water injected should be that amount sufficient to maintain a flow of steam with the formation fluid produced into the well 18. Naturally, the water injection amounts cannot be so great as to extinguish the combustion front. Generally, the amounts of water need not be great to maintain water-steam saturation conditions downstream of the combustion front so as to produce a flow of steam to the well 18. The permissible amounts of water to be injected with the combustion-supporting gas can be determined by laboratory burning tube experiments, utilizing core material and formation fluid from the formation 10. If desired, these laboratory experiments can be supplemented by additional experiments utilizing and testing various water-to-air ratios in the formation 10.

When the combustion front has moved into the immediate vicinity of the well 18, the resulting heating effects in the well 18 become so great that elevated temperatures are obtained which make it difficult to adjust the flow of combustion-supporting gas to prevent combustion of formation fluid in the well 18. At this time, cooling fluid may be introduced into the well 18 through the port 34 in a suitable flow to commingle with, and cool,

the produced formation fluid removed through the conduit 33 to the earth's surface 13. However, this arrangement can produce oil and water emulsions which are difficult to separate. This emulsion problem may be reduced by not using a cooling fluid in the well 18. In accordance with the present method, the production of formation fluid from the well 18 may be terminated for a period of time. The period extent is determined by a decrease in temperature in the well 18 below the elevated temperature where combustion of formation fluid is encountered. The reduction in temperature within the well 18 in many instances need not be of great extent. For example, the heat-thinned formation fluid, as a liquid, will quickly resaturate the area adjacent the well 18, particularly the flow channel 37, by gravity drainage from the upper section of the formation 10. A large quantity of liquid-formation fluid is therefore made readily producible into the well 18. At this time, formation fluid is again produced from the tubing 33 of the well 18. The quenching effect of the liquid-formation fluid greatly reduces the temperature within the well 18. Therefore, the production of the formation fluid may be maintained for a substantial length of time before elevated temperatures are again obtained. Upon the occurrence of undesired elevated temperatures, the well 18 may be again "shut in" by termination of the production of formation fluid through the tubing 33.

It will be apparent that, where the vertical dimension of the formation 10 is very substantial, the preceding steps may be practiced at different horizons in successions, or conjunctively, as is desired. In certain instances, it may be desired to practice the steps in a different arrangement or order. Such alterations in steps are within the scope of the present invention. Additionally, the present description is illustrative of this invention, whose scope is to be defined by the appended claims.

What is claimed is:

1. A method for the recovery of viscous-nonflowing hydrocarbons from formation fluid contained in a subterranean formation residing below the earth's surface comprising the steps of:

- (a) forming spaced first and second well means into the earth,
- (b) arranging said well means for fluid communication between the earth's surface and said formation, said first well means permitting fluid flows to the lower portion of said formation at a restricted horizon and said second well means permitting fluid flows to the lower 30 to 60 percent of the vertical extent of said formation,
- (c) forming a horizontally oriented highly permeable flow channel through the lower portion of said formation extending from said first well means at the restricted horizon to said second well means, said flow channel providing ready fluid communication through said formation between said well means,
- (d) injecting steam through said first well means to pass into said flow channel until said steam has heated said flow channel, said steam injected in a sufficient amount that steam flows from said flow channel into said second well means, and then injecting steam through said second well means to pass through said flow channel until steam flows into said first well means,
- (e) producing fluid from said first well means, during steam injection into the second well means, at a rate not substantially less than the rate at which fluid is being produced thereinto to maintain a minimum back pressure against fluid entering said first well means from said formation,
- (f) injecting a combustion-supporting gas, through said first well means into said flow channel, in an amount sufficient to flow into said second well means and to displace formation fluid from said flow channel thereby maintaining its high permeability to fluid

flows; and maintaining said formation, adjacent said flow channel at a location between said well means, at said elevated temperature so that carbonaceous matter undergoes ignition for creating a forward in situ combustion front therein,

(g) adjusting the flow of said combustion-supporting gas, while moving said combustion front toward said second well means, to maintain a continuous flow of said combustion-supporting gas, the combustion products thereof, and displaced formation fluid, into said second well means at a temperature between about 200° F. and the elevated temperature where combustion of produced formation fluid occurs in said second well means, and

(h) producing formation fluid from said second well means and recovering hydrocarbons from said fluid.

2. The method of claim 1 wherein the amount of hydrocarbons recovered from said formation fluid in step (h) is measured, and the flow of said combustion-supporting gas is varied, between the amounts of flow described in step (g), to secure maximum production of recoverable hydrocarbons from a minimum flow of said combustion-supporting gas.

3. The method of claim 1 wherein in step (g) the temperature created in said second well means in response to the adjusted flow of said combustion-supporting gas is between the steam-water equilibrium temperature in said second well means and the temperature where significant combustion of produced formation fluid occurs.

4. The method of claim 1 wherein water is injected into said first well means during the period when injection of said combustion-supporting gas moves said combustion

front toward said second well means, and said amounts of water are sufficient to maintain a flow of steam with said produced formation fluid into said second well means.

5. The method of claim 1 wherein the production of formation fluid into said second well means is terminated at a time when the approaching combustion front is heating said well means to such elevated temperature as to make difficult an adjustment in flow of said combustion-supporting gas to prevent combustion of formation fluid in said second well means, and then producing said formation fluid, after the temperature in said second well means is substantially reduced, until the temperature rises in said second well means to indicate combustion of formation fluid is again to occur.

References Cited

UNITED STATES PATENTS

20	2,880,802	4/1959	Carpenter	166—11
	2,901,043	8/1959	Campion et al.	166—11
	3,149,670	9/1964	Grant	166—11
	3,167,120	1/1965	Pryor	166—11 X
	3,167,121	1/1965	Sharp	166—11
25	3,209,822	10/1965	Marberry	166—2
	3,221,813	12/1965	Closmann et al.	166—11
	3,227,211	1/1966	Gilchrist	166—11
	3,246,693	4/1966	Crider	166—11 X
	3,280,909	10/1966	Closmann et al.	166—11 X
30	3,369,604	2/1968	Black et al.	166—40

STEPHEN J. NOVOSAD, *Primary Examiner.*