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P. D. BEHNING ET AL.

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OIL RECOVERY BY UNDERGROUND COMBUSTION

Filed May 14, 1953

3 Sheets-Sheet 1

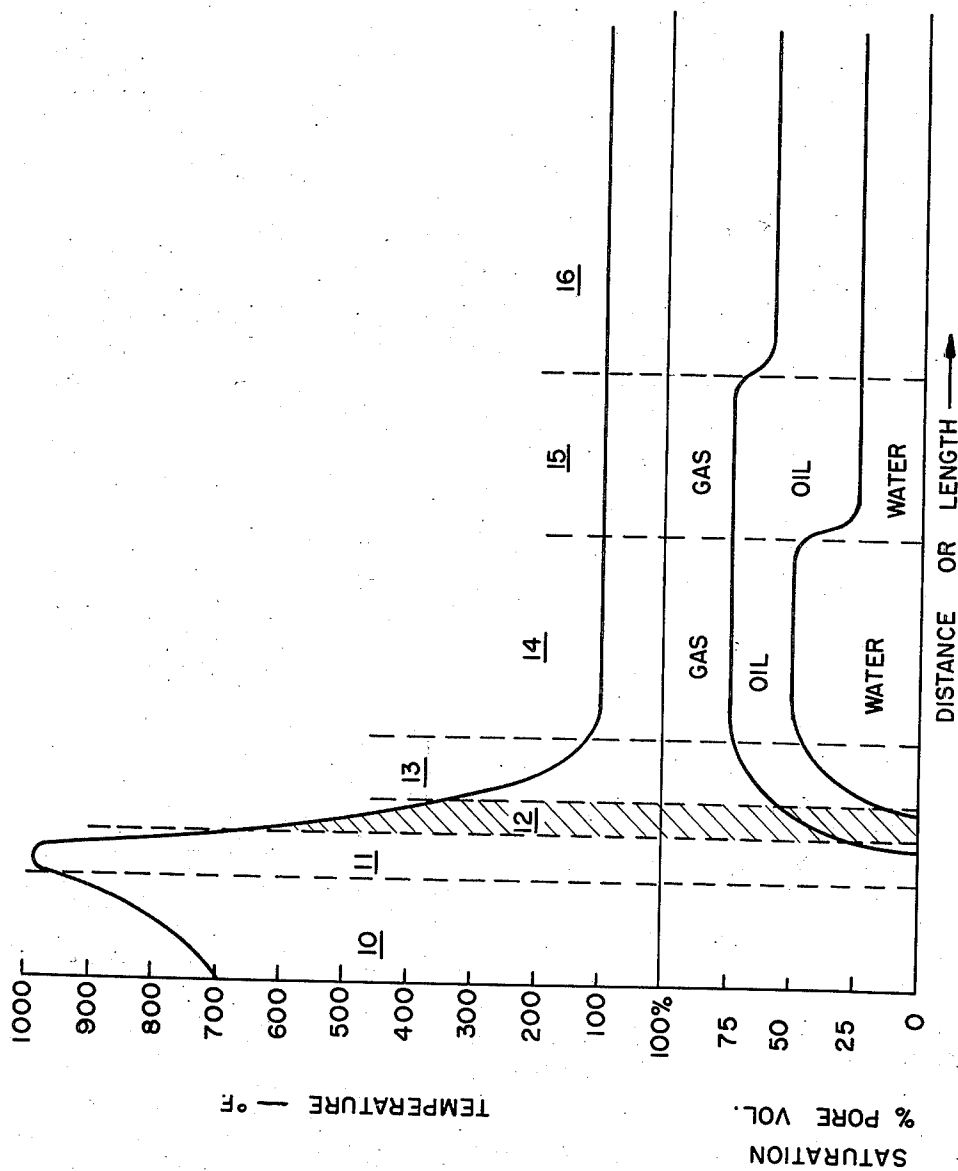


FIG. 1

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3 Sheets-Sheet 2

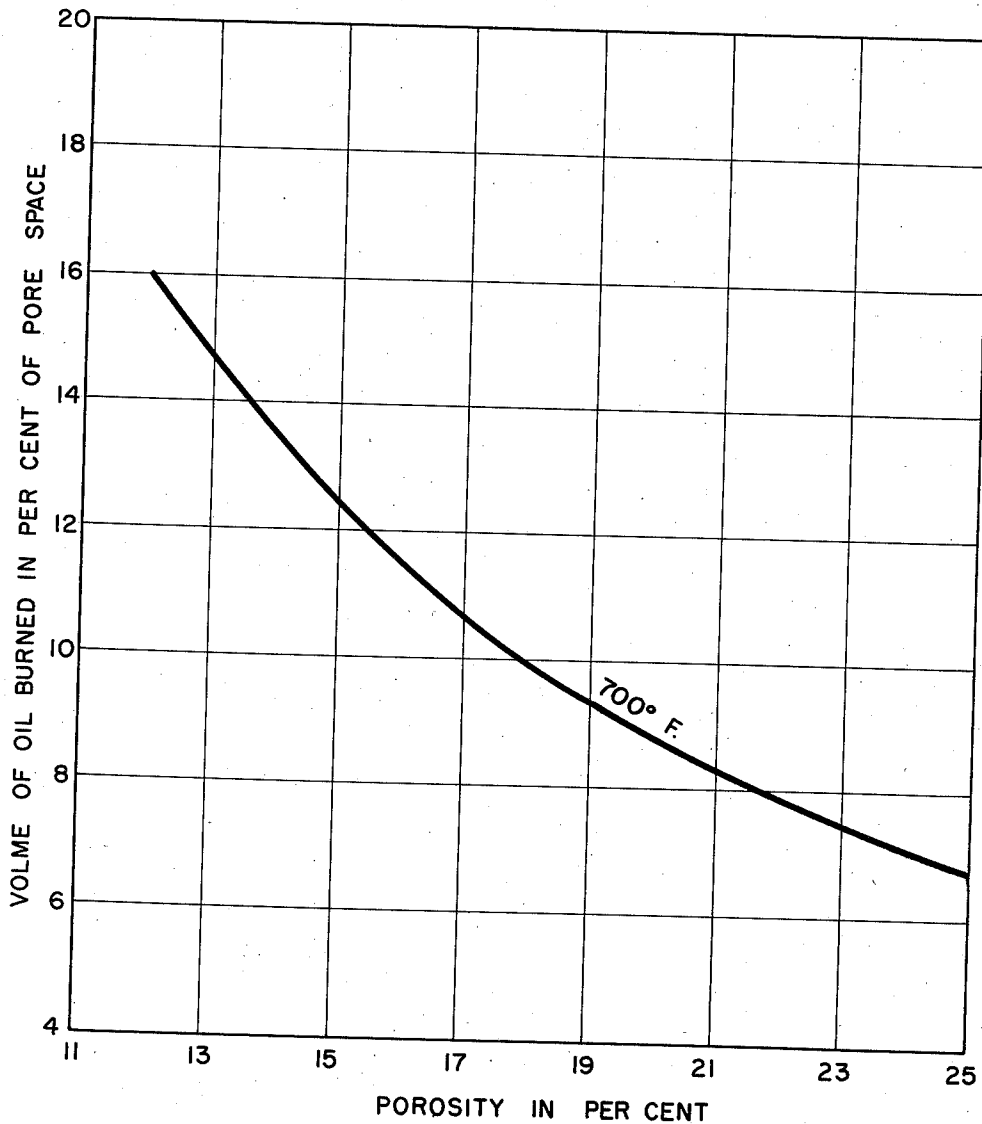


FIG. 2

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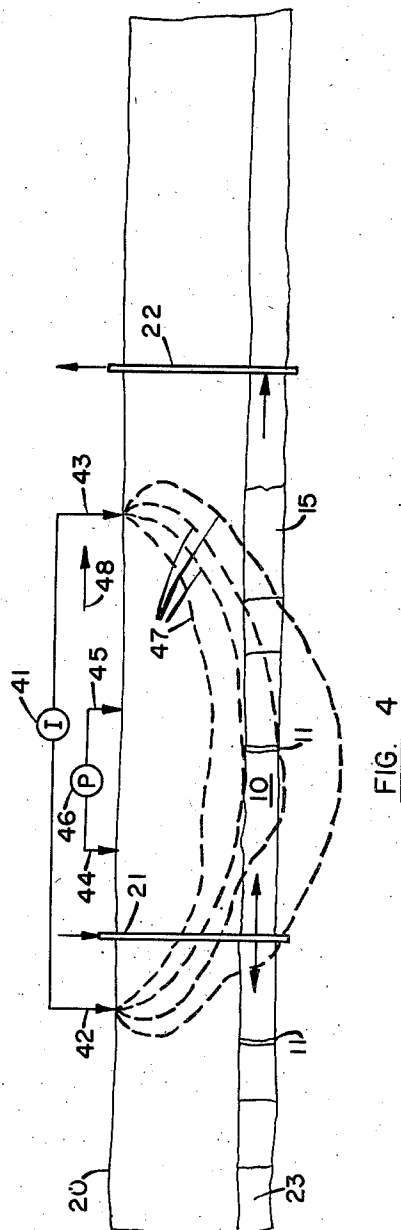
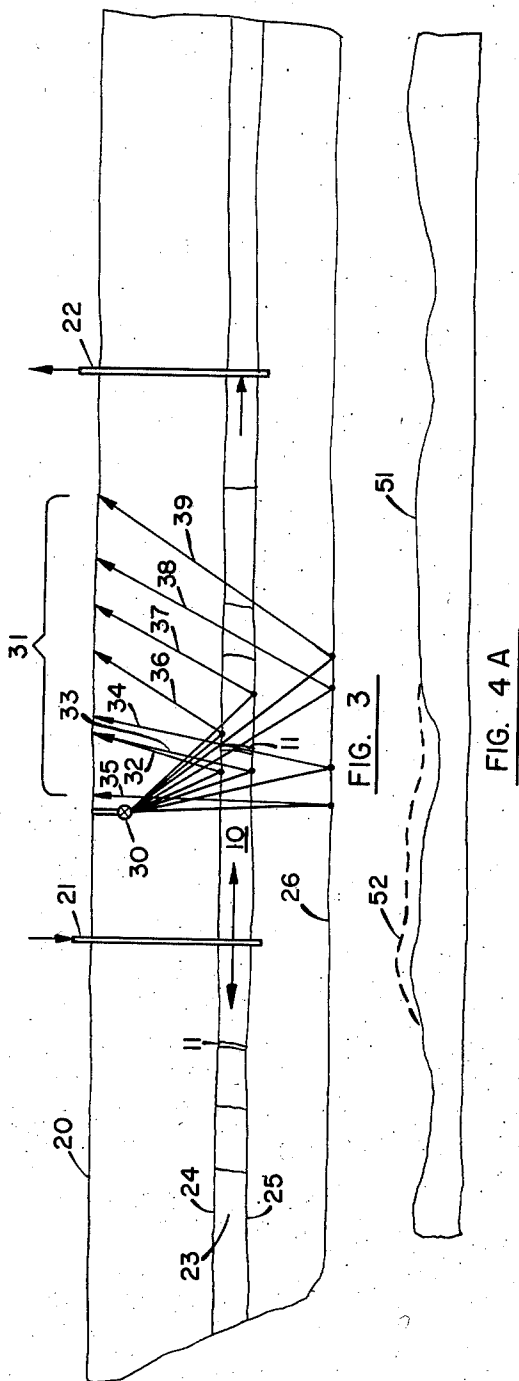
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3 Sheets-Sheet 3.



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OIL RECOVERY BY UNDERGROUND COMBUSTION

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2 Claims. (Cl. 166—4)

This invention relates to the recovery of oil from the underground strata in which it occurs, and is directed particularly to improvements in those recovery processes in which a portion of the oil in place is burned in order to drive out the remainder of the oil by the combined effects of the heat of combustion and the pressure of the combustion products. Specifically, the invention pertains to improvements in the measurement and control of the progress of a combustion recovery process in the underground strata.

It is well known that the methods of oil recovery heretofore most commonly employed utilizing either or both natural and artificially applied energy often leave behind a part of the original oil in place which is as large as or larger than the portion that is produced. Thus, at the end of economic recovery by conventional methods there is often known to be present in many oil-producing reservoirs extremely large amounts of oil which would be highly valuable if any substantial parts of them could be recovered with reasonable additional expenditures. The recovery of some of this oil by the combustion of a portion of it has been proposed, but this process has so far been tried only on an extremely limited scale. Among the difficulties encountered are the determination of the proper rates of introduction and proper concentration of combustion-supporting gas, and the measurement of the resulting progress of the underground combustion zone, which is necessary for making a proper adjustment or variation of these rates and concentrations.

It is, accordingly, a primary object of our invention to provide a method of conducting an underground combustion operation with increased efficiency, principally as a result of being able at any desired time to locate the position of the zone of combustion so that the oxidant-injection rate and/or concentration can be accordingly adjusted or varied from time to time as needed. Another object is to maintain the oxidant-injection rate at all times at an optimum value within certain essential limits. Still another object is to maintain the oxidant-injection rate at an optimum value dependent upon the heat-transfer characteristics of the reservoir and the adjacent rocks. Other and further objects, uses, and advantages of the invention will become apparent as the description proceeds.

In accordance with our invention, the foregoing objects are accomplished by a series of steps which may preferably—but will not necessarily—include as a preliminary step, prior to the beginning of the operation, the installation of most or all of the surface and well equipment to be used in the injection and producing wells. Thereafter, a detailed geophysical survey of the surface area overlying the reservoir to be subjected to combustion recovery is performed by a geophysical method which is particularly adapted to investigate the depth of the stratum to be subjected to combustion. Following this, combustion is initiated at the base of the injection well or wells, and by introduction of oxidizing gas at the proper rate and concentration a combustion zone or front is caused to propagate through the reservoir away from each injection

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well. Subsequently, at any time during the operation, and preferably whenever exact information on the location of the underground combustion front is needed, the geophysical survey or a portion of it is repeated, preferably occupying the same measurement points as in the first survey, and the differential effects on the geophysical response due to the passage of the combustion front through the underground strata are noted. Following the determination of the location of the front in this manner, a calculation is made of the area of the burning face, and appropriate adjustments are made in the rate of supply of oxidant and the rates of withdrawal from various output wells in such a way as to cause the front to move in the desired direction with the proper velocity. Subsequently throughout the combustion operation the geophysical survey is repeated, and the rate of oxidant supply is accordingly readjusted until the recovery is substantially completed.

This will be better understood by reference to the accompanying drawings forming a part of this application and illustrating certain steps in our process. In these drawings,

Figure 1 is a graph of a typical temperature profile and correlative graphs of fluid saturations found in a stratum, or core simulating a stratum, being subjected to combustion drive;

Figure 2 is a graph of saturation and porosity conditions which must be satisfied to establish and move a combustion front through a reservoir;

Figures 3 and 4 are diagrammatic cross-sectional views of part of an oil-producing reservoir respectively illustrating the application of seismic and electrical geophysical surveying methods to the problem of locating the underground combustion front; and

Figure 4a is a graph correlated in position with Figure 4 and showing changes in apparent resistivity due to movement of the underground front of Figure 4.

Referring now to these drawings in detail, it is believed that the significance of the invention and its various steps will be more easily understood when the conditions existing in the various portions of a reservoir stratum being subjected to recovery by underground combustion are set forth. Accordingly, Figure 1 illustrates the various different and distinct zones existing in a typical underground combustion operation. In this figure, it is assumed that the direction of motion of fluids is away from an oxidant input well at the left of the figure and toward an output well at the right of the figure. Input and output well positions are not shown on this figure, for the reason that, to the horizontal scale shown, they would ordinarily lie considerably beyond the edges of the diagram.

The upper portion of Figure 1 is a temperature profile through the combustion and associated zones, while the lower part shows graphically the fluid saturations existing in the various zones involved, both the temperature and fluid-saturation diagrams being to the same horizontal scale.

Starting at the left of Figure 1, the first zone is the dry zone 10 through which the combustion has already passed. The temperature of this zone decreases toward the left in the direction of the input well, since its initially high temperature due to the combustion declines due to heat conduction through the rocks and due to heat transfer to the oxidizing gas passing through on the way to the combustion zone.

Next is the combustion zone 11 where the peak temperature is found, which is typically of the order of 1,000° F. This temperature is generally high enough to insure that all readily vaporizable liquids are in the vapor state. Accordingly, the liquid saturations at the highest temperature portion of this zone are zero, and the gas saturation is one hundred percent.

It is this zone that the reaction between the oil and the introduced oxidant occurs. The oil which is here vaporized and serves as fuel is believed to be that trapped and left behind by the water bank ahead of or downstream from this front. At the front or downstream edge of this combustion zone 11, the water which trapped off this oil is being vaporized and flows ahead in the form of steam, along with the combustion products and the portion of vaporized oil which is not reacted with oxygen. Although the temperature falls off rapidly from the maximum of about 1,000° F. in the downstream direction from the combustion zone 11, oxidation appears to occur over most of this zone. It is at the forward edge of this zone, where the temperature is lowest, that liquid saturations of oil and water begin to be found. The oil saturation here is chiefly that which has been trapped or bypassed by the driving water and left behind for fuel, while the water is partly connate and partly that condensed from steam generated by the combustion. An outstanding characteristic of this zone is the fact that it is very narrow, being from a fraction of an inch to only a few inches in thickness in a typical case.

Downstream from or ahead of combustion zone 11 is a transition zone 13 in which the liquid saturations are changing rapidly due mostly to the condensation of vapors. Accordingly, zone 13 is most appropriately called a "condensation" zone, which is the term that will be used hereafter. The temperature across zone 13 falls off rapidly to the normal bottom-hole temperature within the reservoir.

The exact boundary between zones 11 and 13 is not too distinct, as is indicated by the shaded section 12, since there may be some condensation of heavy oil components occurring while the last traces of oxygen are being consumed. Condensation of most of the unburned vaporized oil to add to the oil saturation due to trapped oil in place is to be expected here because of the declining temperature across this zone. This is opposed, however, by the vaporization of a large portion of the lighter oil components occurring upon the condensation of the steam, which is evidenced by the very large increase in water saturation. The result is a steam distillation of the trapped and the condensed oil which moves the lighter oil components downstream where they condense, and leaves the heavier components behind for fuel. Consequently, the composition of the oil varies markedly across zone 13, the flowing oil saturation which moves ahead, containing a major proportion of the light components of the oil in place, being what may be termed a reduced crude.

Ahead of this declining-temperature condensation zone 13, the water from the steam accumulates in a cool-water zone or bank 14. Gas and water and some of the oil are flowing in this bank, and the relative saturations throughout the bank are nearly constant. As more and more steam condenses throughout the duration of a combustion recovery project, this bank continues to grow in length. The cool water here traps off some of the oil in place, a considerable portion of which—particularly the heavier components—is what is left behind as fuel for the combustion zone 11.

That part of the oil which is not trapped is driven ahead and forms an oil zone or bank 15, which moves ahead due to the combination effect of the gas and water drive. In this zone, normally only the oil and gas phases will be flowing, the water saturation shown here in Figure 1 being simply the connate water existing in the reservoir. Like the cool-water zone 14, oil zone 15 also increases in length as the combustion project progresses.

To the right of oil zone 15, the oil and water saturations of the zone 16 which extends to the output well are generally the liquid saturations existing in the reservoir before the initiation of the combustion project. The gas phase, however, includes both reservoir gas and gaseous products of combustion.

In the course of a recovery operation of this type it is generally noted that the lengths of the water zone 14 and of the oil zone 15 both increase as the combustion zone moves, while condensation zone 13 remains approximately constant in thickness. The combustion zone 11 also tends to remain very small in thickness, and the reservoir rock behind it is observed to be almost completely dry of any liquid.

This dry rock is generally also considerably altered in its mineral character due to the fact that the sedimentary formations which are normally oil-bearing, having never been subjected to the action of such temperatures as 1000° F., are accordingly considerably affected by such temperatures. It is in part because we have noted these modifications and have been able to take advantage of them that we are able to control and carry out a combustion recovery operation with increased efficiency.

The temperature of 1000° F. mentioned as typical of a combustion zone does not always occur in practice, however, as it depends on a number of factors such as adequacy of the supply of trapped oil for fuel and upon the heat losses to the adjacent strata, which vary considerably with combustion zone thickness and propagation velocity. It can be shown that for any given set of reservoir conditions and oil characteristics, of the total available heat, the fraction F which is lost to the confining strata above and below the reservoir stratum is directly proportional to the square root of the combustion zone length or thickness L and inversely proportional to the square root of the velocity V of propagation of the combustion zone. In brief, the fractional heat loss

$$F = K \frac{\sqrt{L}}{\sqrt{V}}$$

where K is a constant.

It is believed immediately apparent from this relation that, in operations where heat loss is important as determining whether or not the combustion zone can be made to propagate, the velocity V is the most important factor in determining the magnitude of this loss. In other words, where a combustion front is operating close to the lower limit of operability, the maintenance of V at or above a certain minimum value may be absolutely essential to the successful operation of the project.

We have observed that the exothermic reactions within the combustion front cannot ordinarily be made to begin until an ignition temperature of at least about 400° F. is reached, by preheating the input gases or otherwise supplying heat from an external source of supply. After ignition, the heat released in the reaction raises the temperature of the rock at the zone of combustion to the equilibrium value of around 1000° F. in the typical case; but sometimes, due to lack of sufficient trapped fuel or excessive losses of heat from the combustion zone, the temperature stabilizes at a value considerably under 1000° F.

We have noticed that, when air is used as the oxidant supply, a temperature of 700 F. is about as low a stabilized combustion-zone temperature as will permit the desired propagation of the combustion front. If the temperature in the front drops much below this value of 700° F., the propagation of the front becomes erratic, and the reaction may eventually die out either in certain areas or entirely over the front, thus leaving behind much by-passed or unrecovered oil.

When, due to low porosity or to the presence of insufficient trapped oil for fuel, the temperature stabilizes at too low a value, steps must be taken to minimize heat losses from the front by increasing V in the above equation, or the oxygen concentration in the oxidant gas mixture must be increased, or both. When pure oxygen is used as the oxidant gas, a combustion front can be made to propagate in a stable fashion even though its temperature is considerably below 700° F.

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Figure 2 accordingly presents graphically certain limiting conditions we have observed about the underground combustion process where air is used as the oxidant gas. If heat losses by conduction to the adjacent strata are neglected—which can be done as long as reasonable velocities of propagation of the front, for example, one foot per day and upwards are maintained—this graph shows, as a function of the reservoir porosity, the volume of oil which must be trapped and left behind to be burned as fuel merely for the purpose of raising the temperature of the rock to the 700° F. level of stable operation. This volume of oil is expressed as a percentage saturation, in terms of the percent of available pore space which it occupies. For low porosities in particular, this graph shows that the percentage of total oil available which must be trapped and burned may sometimes be so large that (1) it is difficult to trap and hold in place a sufficient fraction to provide the necessary fuel, (2) the amount of oil left for recovery may be too small to make a project economically feasible, or (3) the supplying of sufficient oxygen to maintain V at or above the necessary value may be difficult due to low permeability.

Figure 2 thus represents an approximate boundary between operable and non-operable conditions, using air as the oxidant. Conditions of reservoir porosity and saturation of oil which can be trapped for fuel which lies well above and to the right of the 700° F. line in this figure represent conditions where equilibrium temperatures in the combustion front higher than 700° F. can be attained, and thus represent stable operations. Conditions close to this 700° F. line become marginal for the use of air as the oxidant medium, and it is then necessary to minimize heat losses to adjacent strata by keeping the propagation velocity V of the front fairly high. Conditions to the left and below this line are either unstable or inoperative, even though heat losses may be neglected, and recovery can therefore be effected ordinarily only by using an oxidant mixture with higher oxygen concentration than normal air.

Figure 2 makes it possible to estimate in advance the possible operability of a combustion project where the reservoir porosity and the oil characteristics important to the trapping of an adequate fuel supply are known. If, for example, the oil-in-place contains less than the necessary percentage of heavy components which will not be distilled off and moved ahead and which will remain behind the condensation zone 13 as fuel, then the combustion recovery process may be feasible. On the other hand, if the heavy oil components are present in only a very small percentage, it is unlikely that a combustion recovery process can be used.

These considerations lead to an estimate of a minimum rate of oxygen supply. If, for example, a porosity range of 12 to 25 percent be considered, then at least about 1.7 standard cubic feet of oxygen, or about 8 s. c. f. of air per hour should be supplied to each square foot of area of the combustion zone in order to bring about a propagation velocity V of about 1 foot per day. For much smaller velocities than this the loss of heat may become important, unless the supply of fuel is so large that excessive heat losses do not matter.

In order to maintain the oxygen-supply rate to all portions of the front above this stated minimum volume per unit time per unit area of the front, it is necessary to know or follow the location of the front in two ways. The general position of the front must be known, so that its total area can be calculated, to arrive at the bulk rate of oxygen injection into the injection well. The particular position of each portion of the front with reference to the injection and the producing wells must be known, so that all portions of the front can be caused to propagate at above the minimum velocity. If, for example, it is observed as a result of tests that the front

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is progressing in one direction much more slowly than in others, there is danger of the combustion dying out in the slow direction. The reason is that the continuous loss of heat from the slowest-moving portion of the front may reduce its temperature in spots to below the 700° F. stable level.

Accordingly, when uneven propagation of the underground front is noted, certain measures of correction can be undertaken. The producing well in the direction of most rapid propagation can be shut in or produced more slowly, or a greater back pressure held on these wells so that a pressure differential is set up in the reservoir, tending to force the oxygen supply in the direction of the more slowly moving portion of the front. Alternatively, or in addition to varying the production rate or back pressure on some of the producing wells, the total oxygen-injection rate into the input well can be increased to insure that the slow-moving portion of the front receives an adequate supply even though other portions are supplied at greater rates than necessary.

The rate of oxygen supply, and in any given case the velocity of movement of the combustion front which is proportional to it, is important also for the reason that it is related to the distance the front can be propagated away from any one injection well. That is, whenever the total amount of oxygen which must be injected through a given input well to maintain the supply above the required minimum at all locations on the front being propagated away from that well becomes greater than can economically be supplied through the well, then new injection wells nearer to the front position must be provided. In any event, the supply pressure to maintain injection through an input well cannot ordinarily exceed the overburden pressure at that depth. Consequently, knowledge of the specific positions of the underground front in each direction from each input well and with reference to each output well is necessary, both for determining the proper total oxygen-supply rate through the well and for determining when to change the injection location. This information is also needed to establish the proper input rate into each new injection well as it is placed in service.

With regard to the optimum concentration of oxygen in the gas supplied to the combustion zone, we have found that this depends upon the fraction of the oil in place which must be burned in order to carry out the process. In the engineering of any given project a calculation is ordinarily made of the residual oil in place, utilizing all sources of available data. For example, an estimate or measurements may be made of the porosity and fluid saturations from cores, cuttings, and well logs. From these and similar sources of information and data, such as the producing history of the reservoir, an estimate can be made of the approximate amount of oil remaining in place.

For the purposes of combustion recovery it is then assumed that at least 1 and preferably about 1½ pounds of this oil per 100 pounds of reservoir rock must be burned in order to furnish, with a desirable factor of safety, the amount of heat required to raise the rock temperature, make up unavoidable losses, and drive out the remaining oil in the reservoir. Then, utilizing the reservoir porosity data, the gravity of the oil, and saturation data or estimates thereof, it can be determined what percentage of the oil in place is required to make up the 1 to 1½ pounds of oil to be burned in each 100 pounds of reservoir rock. Thus, if each 100 pounds of rock contains about 5 pounds of oil in its pore structure, then 20 to 30 percent of this oil must be consumed to provide the 1 to 1½ pounds for combustion in recovering the other 3½ or 4 pounds, or 70 to 80 percent.

Generally speaking, it may be stated qualitatively that the higher percentage of oil in place to be burned is, the more concentrated should be the oxygen in the oxidant

gas mixture. It will be found that normal air is satisfactory for a large majority of cases, but where the porosity or oil saturation is low, an oxygen-enriched oxidant mixture may be needed. A reason for this requirement appears to be that, where there is low saturation or a small amount of oil in place which requires a larger portion thereof to be burned, the gases with higher oxygen content produce less sweeping of the reservoir ahead of the combustion front and correspondingly leave more of the oil in place for fuel. Conversely, when a larger percentage of the oil is to be recovered, and therefore less of it is required for fuel, a greater sweeping effect is produced by the larger proportion of inert gases in the oxidizing mixture. This tends to reduce the amount of oil trapped and left behind for fuel.

Before considering the manner of carrying out preliminary and subsequent geophysical surveys according to our invention, it should be pointed out that no essentially new or different geophysical method or technique is involved. In this instance, however, there are present at least two factors which are different from the usual geophysical problem. In this case both the depth and the thickness of the zone of interest are known. Also, since the combustion produces chemical and physical changes or modifications of the underground stratum which are sufficiently great to be detectable at the surface, assuming that the depth is not too great, what is therefore of major importance is not the magnitude of the geophysical data but the changes in the data between the initial and the subsequent surveys. Consequently, the geophysical surveys are particularly designed to provide data emphasizing the change in values between the times of measurement.

Referring again to the drawings, and particularly now to Figure 3 which is a diagrammatic cross-section of the earth, from the ground surface 20 at least one oxygen-input well 21 and one producing well 22 extend to and through an oil-bearing stratum 23 having an upper boundary 24 and a lower boundary 25, which stratum 23 is to be subjected to a combustion oil-recovery process. Underlying the lower boundary 25 at some depth which may be known or unknown is a distinct interface 26 which normally produces a recognizable seismic reflection. Although only the two wells 21 and 22 are shown in this figure, it will be understood that these are representative only, and that any number and arrangement of input wells 21 and producing wells 22 may be used simultaneously. Further, any producing well 22 may subsequently be converted to an oxygen-input well after the underground front 11, the water zone 14, and the oil zone 15 reach appropriate locations.

This figure illustrates the application of the seismic method of geophysical surveying to the problem of locating the front 11. Thus, a series of continuous seismic surveys along fairly closely-spaced lines, either parallel or radiating from each well, is first run over the area around input wells 21 and output wells 22. The locations of each shot point 30 and spread position 31 at the ground surface should be carefully marked so that both can subsequently be reoccupied. It is further preferred, in conducting both the initial and subsequent surveys, to utilize equipment and techniques having known amplitude-response characteristics, so that changes in the amplitude of the seismic waves traveling through the dry zone 10, through which the combustion front 11 has passed, can be detected by comparison with the waves transmitted through the same zone before the passage of the front 11.

Although Figure 3 shows only one shot point 30 and one spread position 31, it is to be understood that the preliminary survey will have utilized all possible spread positions which may subsequently be reoccupied. In subsequent surveys, it is obviously necessary only to occupy those positions which will show the exact position of the underground front 10 when its approximate location is already known.

If it happens, by chance, that a reflection of detachable amplitude occurs either at the upper boundary 24 or at the lower boundary 25 of stratum 23, the problem may be considerably simplified. In such event, the reflection coefficient of the interface may be so modified by the combustion temperature that it is necessary only to compare the seismic waves received over the path 32, for example, with those received over the path 36, before and after the passage of front 11 past the reflection point of path 32, to note the change in energy received over the path 32 after passage as compared with that before. Likewise, if reflection occurs from interface 25, comparison of the waves received over path 33 before and after passage of front 11 relative to those received over the path 37 should reveal the location of front 11 as being between the two reflection points of these paths.

It has been observed that the seismic-wave attenuation characteristics of earth strata are strongly affected by their fluid content. Accordingly, the change in physical character of the stratum 23 from being fluid-filled ahead of combustion front 11 to being substantially dry and dehydrated behind the front makes it possible to utilize the amplitude of reflections received from various points of the interface 26. Depending on whether the reflections received from this interface have traveled through the burned zone 10 or the unburned portion of stratum 23 ahead of the front 11, small changes in the observed amplitude should be detected. Thus, it is to be expected that the seismic energy traveling along paths lying between paths 34 and 35, which has been reflected from the interface 26 below layer 23 will have been differently attenuated from that received over paths lying between 34 and 39. In other words, energy traveling in the paths between 34 and 35 will have traversed layer 23 twice and have been subjected to its corresponding attenuation. Waves traveling paths 34 and 38 will have traversed the stratum 23 once through the dry zone 10 and once through the unburned zone to the right of interface 11 where the attenuation is markedly different. Waves traveling paths between 38 and 39 will have traversed only the portions of stratum 23 which are fluid-filled and have not been subjected to the action of combustion front 11. Therefore, by utilizing seismic receiving and recording equipment with known response characteristics, comparisons made of the relative responses along the length of spread 31 before and after the passage of combustion front 11 will reveal the position of the combustion zone 11.

It is believed obvious that the spacing of the individual seismic detectors in the spread 31 is chosen with a view to the required precision with which the position of front 11 is to be ascertained. The closer the spacing of the individual seismometers, the more exact can be the determination of the underground front location.

An alternative method of determining the location of front 11 is shown in Figure 4, which illustrates an application of electrical resistivity prospecting to the problem. This method is applicable particularly to operations where the depth of stratum 23 is not excessively large. For both the primary and subsequent surveys, it is preferred to use identical electrode configurations and to occupy the same electrode locations on the earth's surface. Thus, each survey is carried out by introducing electrical current from a source 41, such as a battery or generator, into the earth's surface 20 through electrodes 42 and 43 spaced apart a distance which is preferably approximately three times the depth of the stratum 23. The potential resulting from current flow in the earth between electrodes 42 and 43 is detected by potential electrodes 44 and 45, preferably spaced apart by a distance about equal to the depth of stratum 23 and centered between the current input electrodes 42 and 43. The detected voltage is indicated or recorded by a potentiometer or meter 46.

In carrying out a survey, the spacings of all of the electrodes are preferably maintained constant, and the entire configuration is moved across the prospect in the

direction of arrow 48, taking readings at points fairly closely-spaced from each other. A resultant apparent resistivity profile is shown in Figure 4a above Figure 4, correlated in position with the diagram of Figure 4. The solid line 51 is typical of the profile obtained on the first or initial survey, the variations on this curve being due in part to the effects of casing and tubing in the wells 21 and 22, or to surface pipelines or resistivity variations in the near-surface strata. The specific variations on curve 51, however, are in themselves without particular significance here.

A subsequent survey to locate the position of underground front 11, however, while it is subject to the same lateral surface variations as the survey producing profile 51, is additionally subject to the high resistance of the dry zone 10 left behind by the advance of combustion zone 11. Since it is well known that the resistivity of rocks and earth is largely affected by their fluid content, the dry zone 10 thus possesses an extremely high apparent resistivity and results in distortion of the lines of current flow 47 in a manner suggested by Figure 4. Since these current lines tend to avoid or to take the shortest path through the burned zone 10, the resultant apparent resistivity recorded at the surface is increased, and the profile 51 is modified as indicated by the dotted line 52 over an interval which corresponds approximately with the extent of the dry zone 10 between the positions of the front 11. Consequently, the progress of the front 11 in any direction from the well 21 can be determined by re-running a portion of the particular resistivity profile line along which the information is desired.

In spite of the large percentage of oil content in the oil bank 15, the presence of connate water in the reservoir prevents the resistivity at that portion of the stratum 23 from being anywhere near the same order of magnitude as the very high resistivity of dry zone 10 surrounding well 21.

In order to carry out electrical resistivity surveys with the accuracy desirable, it is generally necessary that surface pipelines connecting the equipment used in the combustion project be both coated and wrapped with insulating coverings. Also, a generous number of insulating flanges between various sections of the system are desirable to provide electrical separation of the various units. When this is done, the adverse effects of surface pipelines on the resistivity surveying method are minimized, and it is possible to carry out measurements with sufficient precision to detect the change produced by the large increase in resistivity of zone 10.

With such a large number of variables— injection rates, oxygen concentration of the input gas, heat loss, composition of the reservoir oil, saturation, porosity and porosity distribution, back pressure on producing wells, and the like—to mention some of them, it is not possible to specify any single set of conditions which is optimum for carrying on a combustion operation in a given reservoir. In the foregoing, however, an attempt has been made to indicate the interrelation of some of these variables so that some idea can be gained as to how variation of each of the variables may be expected to affect the progress of an underground combustion operation, assuming that other factors remain relatively constant or vary in some known manner. Accordingly, modifications of our process will be apparent to those skilled in the art, and the scope of the invention, therefore, should not be considered as limited to the specific details set forth, but is properly to be ascertained by reference to the appended claims.

We claim:

1. In the recovery of oil from an underground reservoir stratum of known depth and thickness and having a porosity of from about 12 to about 25 percent, by a

process involving combustion of a portion of the oil in place, the steps of making at the earth's surface overlying said stratum an initial set of measurements of a seismic-wave-transmitting property of said stratum susceptible to being altered by the heat of the combustion process, by generating seismic waves near the ground surface and receiving said waves after reflection at a subsurface interface at least as deep as said stratum; initiating a combustion front within said stratum and maintaining said combustion front therein by supplying through an oxygen input well penetrating said stratum at least about 1.7 standard cubic feet of oxygen per hour to each square foot of area of said front, whereby said front is caused to propagate through said stratum; remeasuring at intervals said seismic-wave-transmitting property by repeating at least part of said set of measurements, and determining and plotting the differences between the initial and the remeasured values of said property so as to show in several directions around said input well the positions of said front forming the boundary of the burned-out zone wherein said property has been altered; noting said front positions and varying the oxygen-injection rate through said input well in accordance with said remeasuring step to maintain the supply rate to all portions of said front at at least about 1.7 standard cubic feet of oxygen per hour per square foot of area of said front as shown by the front positions located by said remeasuring step; and recovering oil from a producing well laterally spaced from said input well.

2. In the recovery of oil from an underground reservoir stratum of known depth and thickness and having a porosity of from about 12 to about 25 percent, by a process involving combustion of a portion of the oil in place, the steps of making at the earth's surface overlying said stratum an initial set of measurements of an electrical property of said stratum susceptible to being altered by the heat of the combustion process, by passing electric current through the ground between electrodes spaced about three times the depth to said reservoir stratum and detecting the resultant electric potential between points spaced by a distance approximately equal to the depth of said stratum; initiating a combustion front within said stratum and maintaining said combustion front therein by supplying through an oxygen input well penetrating said stratum at least about 1.7 standard cubic feet of oxygen per hour to each square foot of area of said front, whereby said front is caused to propagate through said stratum; remeasuring at intervals said electrical property by repeating at least part of said set of measurements, and determining and plotting the differences between the initial and remeasured values of said properties so as to show in several directions around said input well the positions of said front forming the boundary of the burned-out zone wherein said property has been altered; noting said front positions and varying the oxygen-injection rate through said input well in accordance with said remeasuring step to maintain the supply rate to all portions of said front at at least about 1.7 standard cubic feet of oxygen per hour per square foot of area of said front as shown by the front positions located by said remeasuring step; and recovering oil from a producing well laterally spaced from said input well.

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