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RECOVERING OIL AFTER SECONDARY RECOVERY

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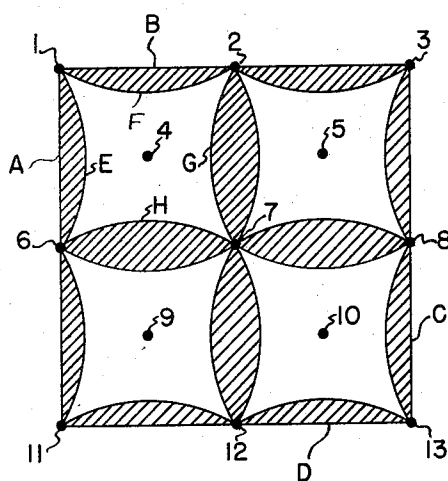


FIG. 1

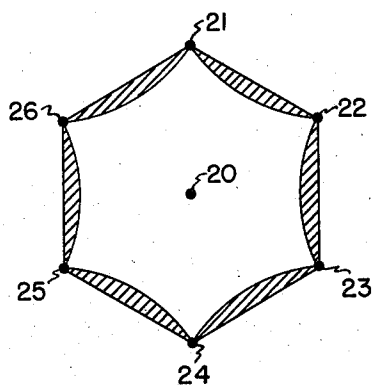


FIG. 2

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RECOVERING OIL AFTER SECONDARY RECOVERY

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2 Claims. (Cl. 166—9)

The present invention is concerned with the increased recovery of crude petroleum oil from subterranean reservoirs when primary production of the reservoirs has ceased. It particularly concerns a method of recovering additional crude oil from a reservoir that has been subjected both to primary production and also to secondary recovery—the latter in the form of water flooding. The invention especially relates to a method wherein an oil reservoir that has ceased primary production is subjected to a particular sequence of liquid and gas drives in order to obtain additional amounts of crude oil from the reservoir.

Before entering into a detailed discussion of the present invention, it is considered necessary first to briefly review the various procedures that are conventionally employed in recovering petroleum crude oil from underground reservoirs. It is well known for example that oil is initially recovered from a new reservoir by relying upon gas or liquid pressure originally within the reservoir to displace oil from the reservoir and up to the earth's surface through one or more wells. It is further well known that the wells which are drilled to tap a reservoir are usually laid out in definite and regular patterns. Thus, one such procedure consists in dividing a given reservoir into a network of squares, each consisting of a certain number of acres, and then drilling a well in the center of each separate plot. In this way the wells are regularly and evenly spaced in orderly rows.

Once the reservoir pressure has dropped to an extent such that it is no longer possible to displace oil from the reservoir at a practicable rate, it has been the practice in the petroleum producing industry to resort to one or more secondary recovery procedures. These procedures for the most part consist in injecting a fluid into one or more wells in any particular reservoir and thereby displacing oil from the injection wells toward adjacent producing wells in the same reservoir. Fluids that are used or have been suggested for this purpose include water, brine, aqueous solutions containing additives such as surface active agents, liquefied petroleum gas, carbon dioxide, air, hot gases of combustion and the like. The fluid that is probably most widely employed for this purpose is water, and it is this fluid with which the present invention is particularly concerned.

When water is used to flood an oil field in a secondary recovery procedure, it has been determined that the water drive is not completely effective in recovering all of the oil that is left in the field following the primary production stage. At this point it is well to note that from 60 to 80 percent of the oil in a given field or reservoir is usually left within the reservoir after primary production has ceased to be feasible. It has further now been determined that only up to about 50 percent of the remaining oil is recoverable by secondary recovery in the form of water flooding. It is apparent then that a considerable amount of oil still remains in most reservoirs even though primary and secondary recovery techniques have both been completely utilized.

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It is accordingly an object of the invention to obtain additional amounts of oil from an oil field or underground reservoir where primary production is no longer economical or feasible. It is a further object of the invention to improve upon the yields of oil that are attainable by the use of the water flooding method of secondary recovery.

The aforementioned objectives are best realized in accordance with the present invention in a manner that is best described by reference to the drawings that form part of the description.

Figure 1 illustrates the conventional so-called 5-spot pattern which is often employed in water flooding programs.

Figure 2 illustrates still another pattern that is occasionally employed in water flooding programs. This particular pattern is conventionally referred to as the 7-spot pattern. The illustrations in both figures may be considered to be essentially top views of a portion of a reservoir or field.

Referring first to Figure 1, the individual wells illustrated there are indicated by the numerals 1–13 inclusive; and the line boundaries of the entire section are designated by the legends A, B, C and D.

It is apparent in Figure 1 that the wells 1–13 inclusive have been laid out in a regular pattern of squares; and it will be assumed for the purpose of the present description that the field or reservoir illustrated in the figure has ceased primary production. It will further be noted that wells 4, 5, 9 and 10 have been converted to injection wells for carrying out a water-flooding program. The particular flooding pattern that is illustrated in Figure 1 falls within the so-called 5-spot category wherein a fifth well in the geometric center of a square formed by four surrounding wells is converted to an injection well for the introduction of water within the reservoir.

Parts of Figure 1 have been shaded to depict the results that are obtained when water flooding is practiced using the 5-spot flooding pattern. Referring specifically to the square area defined by lines A, B, C and D, it will be observed that additional lines E, F, G and H are also shown extending from each one of the four corner wells to the next adjacent well. These curved lines are intended to illustrate the sweeping results that are obtained when using water flooding in this type of a flooding pattern. The existence of the lines may be explained in the following manner.

Water flooding is commenced in the field or reservoir of Figure 1 by injecting water into wells 4, 5, 9 and 10. As the water enters each of these wells, it gradually spreads throughout the formation in a gradually widening area displacing a bank of oil before it. Referring specifically to well No. 4, the water flooding area occasioned by the injection of water into this particular well has increased in area until water as well as oil has been displaced into the surrounding producing wells 1, 2, 6 and 7.

During the initial stages of the water injection step, oil alone is displaced into and withdrawn from wells 1, 2, 6 and 7. During the last stages of the flooding program, however, both water and oil are recovered from these wells; and the flooding program is eventually discontinued when the ratio of water to oil obtained from the wells is so great as to be economically unattractive or impractical. Generally speaking, a water flooding operation is discontinued when this ratio exceeds a value of about 50 to 1 to 100 to 1; and at this point the field or reservoir is usually abandoned.

It is apparent from Figure 1 that a very considerable portion of the reservoir or field in that figure has neither been swept nor contacted by the water flood. This unswept portion, which is depicted in the figure by the

shading lines, will generally constitute approximately one-fourth of the total volume of a reservoir—a fact that has been ascertained both by theoretical and model studies.

The unswept portion of the reservoir of Figure 1 consists essentially of slender elliptical-type sections that extend from one producing well to the next adjacent producing well. Thus, the unswept portion of the reservoir forms a regular latticework within the reservoir; and it is generally richer in oil than was the original reservoir formation.

In accordance with the present invention, the unswept sections of the field or reservoir in Figure 1 are subjected to a liquefied petroleum gas drive when the water flooding program has been completed. This "tertiary recovery" procedure is carried out in the following manner. Liquefied petroleum gas (hereinafter designated as LPG) such as liquefied propane, butane, or pentane is injected into alternate producing wells of the secondary recovery pattern and is followed by the injection of a non-condensing gas such as methane, air, natural gas, hydrogen, etc.

Referring specifically to the figure, LPG is injected into wells 1, 3, 7, 11 and 13. In other words, it is injected into every other producing well, each such well being located at one end of an unswept section of the overall field or reservoir. Thus, there is at one end of each unswept section in the field or reservoir an injection well for the injection of LPG; and there is at the opposite end of each such unswept section a second well for the production of additional crude oil. It will be noted that each one of the original water-injection wells is capped or otherwise shut down before starting the injection of LPG. At this phase of the operation, then, the water injection wells 4, 5, 9, and 10 are shut down; wells 1, 3, 7, 11, and 13 are LPG injection wells; and wells 2, 6, 8, and 12 remain production wells.

The amount of liquefied petroleum gas that is injected into a field or reservoir as a whole may constitute up to about 15 volume percent of the hydrocarbon pore volume in the unswept sections of the reservoir or field. This total amount is generally distributed substantially uniformly throughout the new injection wells. It is particularly preferred that from about 7.5 to 15 volume percent of LPG (based on the hydrocarbon pore volume of the unswept area) be injection in this manner; and it is further preferred that the LPG be propane or butane and especially propane.

When injecting LPG within the new injection wells, it is essential that the liquid be injected at a rate such that it travels through the unswept sections at a rate not in excess of a few feet per day. The precise rate for any given well will depend upon such factors as the thickness, permeability and fluid saturation of the reservoir and the viscosity of the oil. This rate may be readily maintained by controlling the pressure under which the gas is injected within each one of the injection wells.

It is well to note at this point that the injection pressure of the LPG must always be at least sufficient to keep the gas in the liquefied condition within the reservoir. For example with a reservoir temperature of about 120° F. it is necessary to maintain a reservoir pressure of at least about 250 p.s.i.g. when using propane in order to keep the propane liquefied. Details of this nature are well understood and readily attained by persons skilled in the art.

Once the LPG has been injected into the appropriate injection wells, a bank of non-condensing gas is thereafter injected into each one of the same wells in order to drive the propane through the unswept sections. Gases that are suitable for this purpose are generally characterized by being cheap and plentiful, non-corrosive to metal equipment, and non-harmful to the reservoir or to the hydrocarbons in the reservoir. As mentioned earlier, suitable gases include methane, carbon dioxide, air, the chemically inert gases, etc. An especially preferred gas

is natural gas, since it is generally available in producing areas at relatively high pressures.

As in the injection of the LPG, it is desirable that the non-condensing gas be injected into each one of the injection wells at a rate such that the bank of LPG moves through the unswept portions at a rate less than about 5 feet per day and preferably less than about 2 feet per day. Once again details of this nature will be readily apparent to persons skilled in the art.

Injection of the non-condensing gas may be continued until the ratios of gas to propane and/or gas to oil that are obtained from each one of the producing wells are so great as to render the operation economically or physically unattractive. At this point the operation may be discontinued.

The afordescribed procedure is considered to have application both to oil fields that are about to be subjected to secondary recovery techniques and also to fields where water flooding has already been practiced. The procedure is therefore doubly valuable in that it can be used on oil fields and reservoirs that have just recently been water flooded or that have ceased primary production and also to fields and reservoirs that have been subjected to water flooding in years past.

To recapitulate briefly, an oil reservoir that has ceased primary production is initially subjected to a water flooding program wherein nonadjacent producing wells in the reservoir are converted to injection wells for the introduction of water within the reservoir. The wells that are immediately adjacent each injection well are retained as producing wells in order to recover the oil that is displaced by the water drive.

Once the water flooding program has been interrupted as being no longer practical or economically feasible, alternate producing wells in the water-flooding operation are then converted to injection wells for the introduction of liquefied petroleum gas within the reservoir. The LPG in turn is followed by the introduction of a non-condensing gas which serves to drive the LPG and oil before it. The LPG and additional oil are withdrawn from the reservoir by means of the producing wells that have been retained for use as such. This phase of the overall process is continued until negligible or uneconomical amounts of oil and liquefied petroleum gas are recovered.

It is well to note at this point that—as indicated earlier in this description—the position in the reservoir of the water injected during the water flooding step is such as to impose restrictive boundaries on the tertiary recovery LPG project, thereby creating linear reservoir sections to which the solvent extraction technique is considered to be most applicable. It might appear that injection of LPG into a watered-out well might not be feasible due to the water-blocked or water-logged condition of the reservoir immediately around the well bore. Due to the low viscosity of liquefied petroleum gas and of gases that are used for gas drives, however, ($\frac{1}{10}$ and $\frac{1}{100}$ that of water, respectively) adequate injectivity of these two fluids can readily be obtained. An example of reservoir acceptability to fluids such as these is afforded by data obtained from an actual well. Core analyses of this well indicated a permeability of less than 1 millidarcy with water saturations averaging 85 percent. Relative permeability to other fluids of this degree of water saturation would be essentially zero, but in spite of this fact up to 400 barrels of liquefied petroleum gas per day were injected at reasonable injection pressures.

Once the LPG has pierced the water immediately next to each injection well, it will be noted that the bank of liquefied petroleum gas can be readily controlled and moves preferentially from the injection wells directly toward the producing wells instead of into the water-filled portion of the reservoir. It is a well known fact that the presence of water in an oil reservoir formation greatly reduces the permeability of the formation toward hydrocarbon materials such as crude oil or LPG. It follows then

that the areas of a reservoir that have been flooded with water are generally much more resistant to the flow of LPG than are the areas that have not been swept by the water. The precise amount of LPG that will flow through the unswept sections in preference to the swept sections will depend upon the relative mobilities of the sections; and the mobilities in turn will be influenced largely by the viscosities of the fluids displaced in the sections and the relative permeabilities of the sections. It is also contemplated that, since PLG and water are not miscible whereas LPG and crude oil are miscible, the mobility of the propane and oil in the unswept sections improves markedly as the process progresses.

By employing this procedure, it is considered that from 40 to 60 percent of the oil that is left in a reservoir after a water flooding program may now be recovered.

The foregoing description of the invention has been largely restricted to a discussion of the application which the process would have to a 5-spot pattern of water flooding. It is apparent that the invention may also be readily adapted to line drive flooding programs and also to more complex flooding patterns. This fact is readily established by reference to Figure 2 where application of the invention to a 7-spot pattern is illustrated. In this instance water has been injected into a reservoir via well 20 and has displaced oil from the reservoir through producing wells 21-26 inclusive. A water flood, however, has left an unswept segment or section extending substantially between each pair of adjacent producing wells in the reservoir. These sections are depicted by the shaded areas in the figure.

In accordance with the present invention, the reservoir of Figure 2 is further treated by now injecting liquefied petroleum gas and then a non-condensing gas into every other one of the producing wells. For example, the liquefied gas and the non-condensing gas may be injected into wells 21, 23, and 25; and the result of this step is to sweep the shaded areas of oil and to displace the swept oil to the remaining wells 22, 24 and 26 whence the oil is recovered at the earth's surface.

The invention may be even better understood by reference to the following specific example wherein a conventional multi-well reservoir containing an oil of about 5 cps. viscosity may be assumed to have been subjected to a primary production phase or program to the point where about 0.75 pore volume of oil remains in the reservoir. At this point the reservoir may be flooded with water as by means of a 5-spot flooding pattern until the water/oil ratio in the producing wells is more than about 100 to 1. Considering this ratio to be the economic limit in this case, each 5-spot pattern in the reservoir will consist of a large central water-swept area and four smaller linear non-water-swept areas as discussed earlier in this description. The swept area may be 35 percent oil saturated at this point. The unswept sections may comprise about 20 percent of the original 5-spot area and may now to be up to 90 percent saturated with oil, having gained oil from the swept area during the water-flood period. Therefore some 18 volume percent of the original oil in place in the entire 5-spot may still reside in the unswept sections of the area.

Substantially 90 percent or more of the oil that is still within the non-water swept sections of each 5-spot area may be recovered in accordance with the present invention by injecting about 0.1 pore volume of liquefied propane based on the pore volume of the non-swept sections (i.e. about 0.02 pore volume based on the entire 5-spot area) and thereafter injecting a bank of natural gas to drive the propane bank through the area. As explained earlier, the propane and natural gas drives are injected into non-adjacent corner wells of the 5-spot pattern and oil, propane and eventually gas are withdrawn from the remaining corner wells. The well at the center of the 5-

spot pattern is capped or otherwise closed so that no fluids are recovered from this well.

At the outset of the propane injection program, it is contemplated that the mobility of the propane through the swept sections is at least equal to its mobility through the non-swept sections. It is further contemplated that the mobility of the propane through the non-swept sections, however, rapidly improves since the oil within these sections is substantially entirely miscible with the propane while the water in the swept area is substantially immiscible with the propane. Thus, the propane, which at the outset tends to enter the swept water-logged area initially in the present case in about the same volume as it enters the non-swept sections, very soon tends more and more to direct itself selectively through the non-swept sections. And even those portions of the propane that do penetrate into the water-logged area tend to work themselves back toward the non-swept section and thence toward the producing wells, since the water injection well in the center of the entire 5-spot area is closed. In short, it is conservatively estimated that the amount of oil recovered by the propane drive is at least 90 percent of the oil that was left solely within the non-swept sections. It is considered that up to 20 or 30 percent more than this volume may also be recovered from the water-logged area.

It may be seen from this example, which is based on very conservative information and estimates, that the process of the present invention makes possible the recovery of as much as at least about 14 volume percent of the original oil in a reservoir and it may recover up to about 20 percent or more of the original oil. These figures may be further improved upon when the viscosity of the original reservoir oil is less than the 5 centipoise value in the example.

What is claimed is:

1. In a secondary recovery method of recovering oil from a multi-well reservoir in which water is injected into a plurality of wells and oil is withdrawn from the remaining producing wells until the ratio of water to oil produced is impractical and there remain unswept sections of the reservoir that extend between adjacent producing wells, the improvement which comprises closing off the water injection wells, injecting a bank of liquefied petroleum gas into a producing well at one end of at least one of said sections, maintaining a pressure on the section to retain the liquefied gas in liquid form, thereafter driving the liquefied gas by means of a non-condensing gas through the section, and withdrawing oil from the reservoir via a producing well at the opposite end of the section.

2. A method of recovering oil from a multi-well subterranean reservoir wherein water is injected into the reservoir via a plurality of input wells, each said input well being disposed centrally relative to a plurality of production wells, continuing the injection of said water, whereby ultimately sections of the reservoir unswept by the water extend between pairs of adjacent production wells, thereafter shutting down said water input wells, injecting a bank of a liquefiable petroleum gas into a first production well at one end of at least one of said sections, maintaining a pressure on the injected gas sufficient to retain the gas in liquefied form, injecting a non-condensing gas through said first production well so as to drive the liquefied gas through said section toward a second producing well at the opposite end of the section, and withdrawing additional oil from said section via said second producing well.

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