Nov. 22, 1955 L. P. WHORTON ET AL 2,724,437

METHOD OF RECOVERING DESIRABLE PETROLEUM HYDROCARBON FRACTIONS FROM PRODUCING OIL RESERVOIRS

Filed Aug. 7, 1951 2 Sheets-Sheet 1

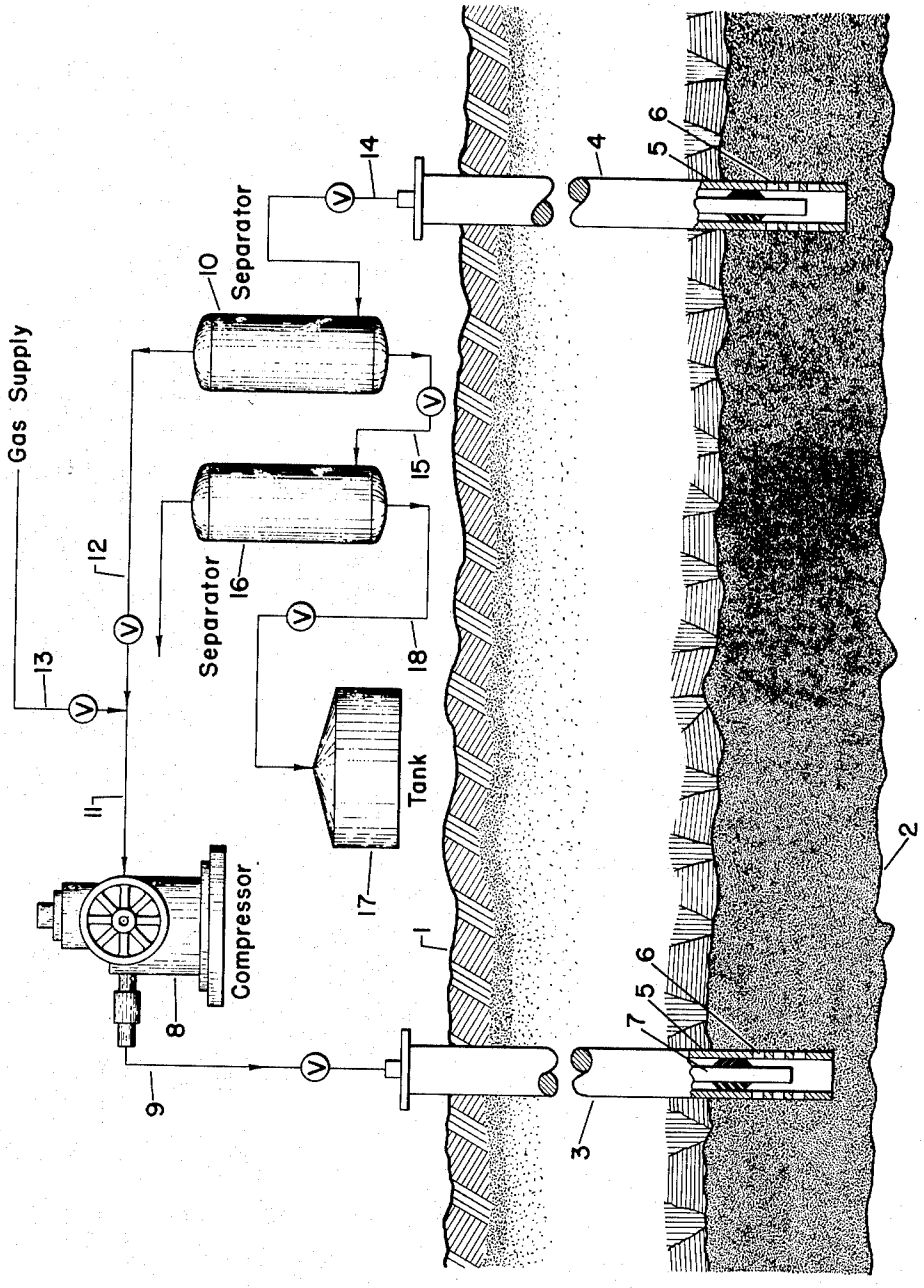


Fig. 1

ATTEST

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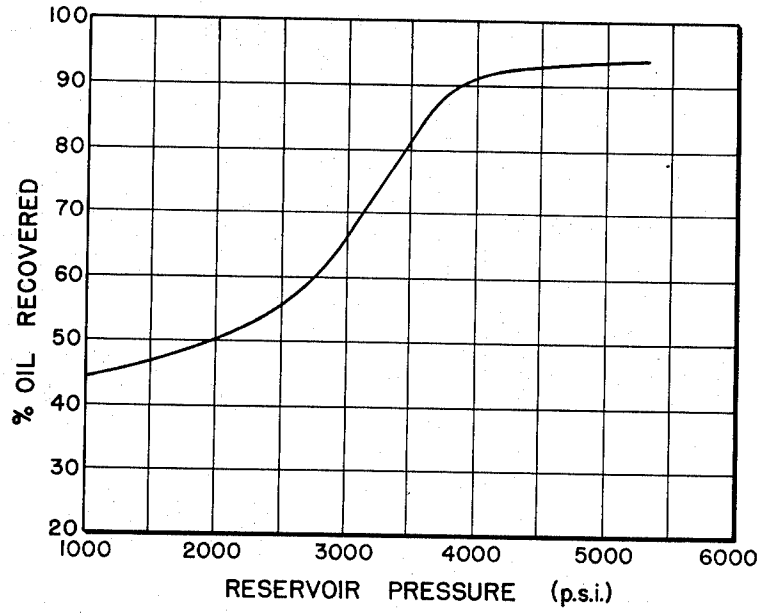


Fig. 2

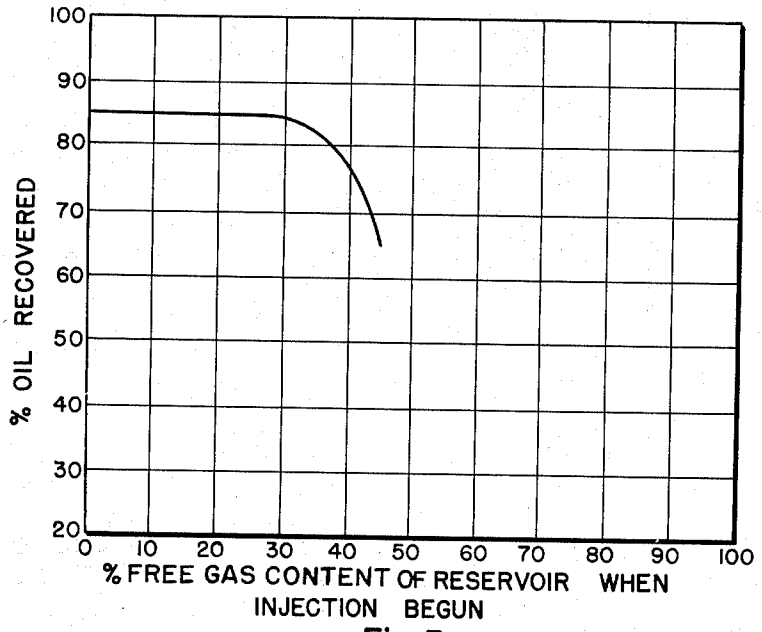


Fig. 3

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METHOD OF RECOVERING DESIRABLE PETROLEUM HYDROCARBON FRACTIONS FROM PRODUCING OIL RESERVOIRS

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2 Claims. (Cl. 166—7)

This invention relates to increasing the ultimate recovery of oil from oil reservoirs, and more particularly to a method of obtaining increased production from such reservoirs by injecting normally gaseous hydrocarbons under high pressure before the reservoirs have become substantially depleted by conventional primary and secondary recovery methods.

This application is a continuation-in-part of application Serial No. 86,414, filed April 9, 1949; application Serial No. 99,650, filed June 17, 1949; and application Serial No. 142,568, filed February 6, 1950, all of which applications are joint applications in the names of the applicants of the present application, and all of which are now abandoned.

In the recovery of oil from a subsurface oil reservoir, it has been the practice heretofore to permit the oil to flow from the reservoir under the force of the native reservoir energy which may be in the form of a water, gas cap, or solution gas drive, or combinations thereof. This production by native reservoir energy, is commonly referred to as "primary recovery." Further, it has been common practice to augment the native reservoir energy either during the early stages of oil production or, more often, after the reservoir has approached its economic production limit by primary recovery methods. This may be accomplished by any one or more of several known methods including gas and water injection to provide artificial pressure drives, and production in this manner is termed "secondary recovery." In providing a reservoir with such a gas or water drive it is conventional practice to inject the gas or water into the oil producing zone while the reservoir is maintained at a relatively low pressure of the order of 1,500 p. s. i. Although these methods of secondary recovery have resulted in an increase in the ultimate recovery of oil over that possible solely by means of primary recovery methods, in some cases only about 20% to 30% of the initial oil in place is recovered and frequently as much as 50% of the oil remains after depletion of the reservoir regardless of the heretofore known method or methods of primary and secondary recovery employed for producing the oil. The practice of this invention which relates to a novel method of producing from oil reservoirs by the injection of normally gaseous hydrocarbons results in the recovery of a considerably greater amount of oil than has been obtainable by heretofore known recovery methods.

At the outset, it should be understood that even though the process described herein involves artificially supplying additional energy to an oil reservoir in the form of high pressure hydrocarbon gases, it is not a "secondary recovery" method in the sense in which that term has come to be used in the art. That is, the method is not designed to obtain merely some additional oil from a reservoir which has been partially or substantially depleted by prior known methods of primary and secondary recovery. Rather, it is concerned with treating a producing oil reservoir early in its production life, and preferably from the very beginning of production. In this respect, the invention deals with an improved method of obtaining oil by injecting high pressure normally gaseous hydrocarbons into a reservoir while it is still a "producing" reservoir rather than first allowing it to become "depleted" by conventional recovery methods.

In practicing the present invention, high pressure normally gaseous hydrocarbons are injected into a producing reservoir which has at least one injection well and one production well. The gas is introduced through the injection well at a pressure which must, of necessity, be greater than existing reservoir pressure. Although there will be other effects, which will be explained in more detail hereinafter, it is obvious that at the start of this injection this gas will, due to its greater pressure, displace some of the reservoir oil in the vicinity of the injection well and it will increase the reservoir pressure in the unswept-out portion of the reservoir, which portion is defined hereinafter. In accordance with this invention there eventually is formed immediately ahead of the injected gas a relatively narrow band of fluid consisting of both enriched injected gas and liquid reservoir oil in which some injected gas has been absorbed. Ahead of this band of fluid is the reservoir oil which is displaced through the reservoir and eventually produced at the production well while the gas is being injected. For purposes of convenience in describing the process of this invention, the portions of the reservoir occupied by the injected gas at any one time shall be referred to hereinafter as the "swept-out portion" of the reservoir. Similarly, the portion of the reservoir occupied by the narrow band of gas and liquid reservoir oil shall be referred to as the "zone of contact." The portion of the reservoir occupied by the reservoir oil shall be referred to as the "unswept-out portion."

In order to clearly understand the features of the process of this invention, the following explanation and definition of terms as used herein is made. Reservoir pressure as used throughout this specification means the pressure which is present in a reservoir, that is, the pressure to which substantially all of the reservoir oil in the reservoir is subjected. This reservoir pressure is usually determined by measuring the pressure at the bottom of a shut-in well drilled into the reservoir.

A producing reservoir necessary for practicing this invention, in its pure virgin state, originally contains fluid in essentially one liquid oil phase. This liquid oil phase consists of various molecular weight hydrocarbons, for example, C_1, C_2, C_3, C_4, C_5, C_6, and C_{7+}. It is well known by those skilled in the art that each of these constituents at normal atmosphere conditions are either in the gaseous or liquid state. For example, C_1, commonly known as methane, is normally a gaseous hydrocarbon while the higher molecular weight hydrocarbons such as C_{7+} are normally liquid hydrocarbons. Therefore, it can be stated that any liquid reservoir oil consists of normally gaseous hydrocarbons dissolved in normally liquid hydrocarbons.

The amount of normally gaseous hydrocarbons which any liquid reservoir oil can hold in solution is directly dependent upon the reservoir pressure. When a new reservoir is discovered, several properties of that reservoir and the oil therefrom are determined in order to plan for its production. One of these properties of the reservoir is the reservoir pressure. Another is the original reservoir saturation pressure. The original reservoir saturation pressure of a given reservoir is the lowest pressure at which all of the normally gaseous hydrocarbons originally existing in such reservoir will remain dissolved in the reservoir oil. A property of the reservoir oil is its original saturation pressure which is equal to the original reservoir saturation pressure. For an example, in a typical reservoir, the reservoir pressure at the time

of its discovery was 4,200 p. s. i. and the original reservoir saturation pressure was 2,780 p. s. i.

In producing an oil reservoir containing essentially only liquid reservoir oil, the liquid reservoir oil exists in the reservoir under such high pressure that upon releasing the pressure the gas dissolved in the liquid tends to expand or escape driving the reservoir oil out of the producing well. Such production is known as solution gas drive production. After reservoirs have been producing by solution gas drive for an extended time, the reservoir pressure will eventually decrease to such an extent that the reservoir pressure will equal the original reservoir saturation pressure. The reservoir oil at this pressure and lower pressures is then considered to be saturated with gas and a reservoir containing this saturated oil is commonly referred to as a saturated reservoir. By the same token, before the reservoir pressure is reduced to below the original saturation pressure, the reservoir oil in the reservoir is considered to be undersaturated and a reservoir containing this undersaturated oil is commonly called an undersaturated reservoir.

After a reservoir has become saturated, the gas dissolved in the liquid reservoir oil continues to come out of solution as the production of the reservoir is continued. This gas will be referred to herein as "free gas." The per cent of free gas present in the reservoir at any one time is then referred to as the free gas content of the reservoir. It should be apparent that as production continues, the reservoir pressure drops and the free gas content of the reservoir increases.

With the above description of the various conditions of the reservoir oil during the production states, it should become evident that after the reservoir oil has become saturated, if the free gas content of the reservoir is not too high, the saturated oil in the unswept-out portion can easily be made undersaturated by means of increasing the reservoir pressure above the original reservoir saturation pressure. The theory behind this phenomenon is that the free gas in the unswept-out portion is pushed back into solution with the liquid reservoir oil.

In some saturated reservoirs, for example, those having a high free gas content, free gas will exist continuously in a path extending through the entire distance of the reservoir between the injection well and the production well. When gas is injected in reservoirs that have an extremely high gas content, injected gas even at high injection pressures will flow as a separate phase through the path that the free gas occupies. Therefore, in these cases when gas is injected into the injection well, the gas will flow independently in one separate gaseous phase through the reservoir to a production well. The minimum free gas content of a reservoir at a given pressure which will enable the independent flow of gas through the entire reservoir is termed the "critical gas saturation" for the reservoir at such pressure. Below the critical gas saturation of a reservoir, injected gas will not flow independently through the entire reservoir at the injection pressure. (For a discussion of critical gas saturation, see Geffens, Owens, Parrish and Morse, Transactions, AIME, 192 (1951) p. 106.) It should be realized that in some reservoirs having a critical gas saturation, the free gas content is relatively low so that an increase in the reservoir pressure incident to injecting gas in the reservoir will cause some of the free gas to go into solution with the liquid oil thus reducing the free gas content of the reservoir to below critical gas saturation. In other reservoirs, such as in the case where there is a gravity segregation condition or an extremely high free gas content, the increased reservoir pressure will not push enough of the free gas of the reservoir back into solution with the liquid reservoir oil and any injected gas will continue to flow through the entire reservoir even at extremely high pressures.

As pointed out above, the method of this invention is applicable only to producing reservoirs as distinguished from depleted reservoirs. A producing reservoir is one in which the unswept-out portion of the reservoir is or may be substantially completely filled with the liquid phase of the exclusion of any appreciable gaseous phase. More specifically, it is a reservoir having a free gas content below the "critical gas saturation" at the injection pressure.

Although a reservoir may be most economically treated by the method of this invention, if treatment is begun early enough in the life of the reservoir that no separate gas phase has appeared therein, the method is applicable to reservoirs which though having a separate gaseous phase prior to the start of the treatment, have such a low free gas content that when the pressure on the reservoir is increased by the injection of gases incident to the practice of the method, the free gas in the unswept-out portion of the reservoir will go back into solution with the liquid phase as explained hereinabove. Thus the unswept-out portion of the reservoir will be essentially completely liquid filled. A "producing" reservoir therefore in its broadest sense, as used in this invention, includes reservoirs which at the beginning of treatment by the method of this invention either contain (1) undersaturated liquid reservoir oil, or (2) saturated liquid oil and a small volume of free gas such that the free gas in the unswept-out portion of the reservoir at the higher reservoir pressure resulting from the injected gas will be pushed into solution with the liquid reservoir oil, thus making the reservoir oil in the unswept-out portion undersaturated, or (3) saturated liquid oil and a volume of free gas such that the free gas content before injection is at the "critical gas saturation" but which upon injecting gas at the pressures contemplated by this invention will have its free gas content reduced to below critical in the unswept-out portion of the reservoir. In contrast, a reservoir which will allow the injected gas to flow through the reservoir from the injection to the production well at the pressures contemplated by this invention is not a producing reservoir within the terminology used herein.

In view of the properties of reservoirs and reservoir oils as previously described, it will be appreciated by those skilled in the art that a producing reservoir in which a gas saturation at critical has developed due to lowering of the reservoir pressure below the original saturation pressure of the reservoir fluid, as might occur when a reservoir is allowed to flow for an extended period of time by solution gas drive, may have its free gas content reduced to below the critical gas saturation by increasing the pressure on the reservoir back up to a pressure equal to or above the original saturation pressure of the reservoir fluid, since the free gas which separated from the liquid upon lowering of the pressure will be re-absorbed by the liquid when the pressure thereon is raised to the value which existed just before the gas began separating. Thus, it will be appreciated that the unswept-out portion of a producing reservoir which, before treatment according to this invention, has a high gas content which is above the critical gas saturation may be caused to become substantially filled with the liquid phase of reservoir fluid to the exclusion of a separate gaseous phase by raising the pressure on the reservoir to or above a pressure equal to the original saturation pressure of the reservoir fluid.

According to present methods of production a reservoir which is found to exist independently of a gas cap or natural water drive might be tapped with one or more production wells to which oil would be permitted to flow under the energy of the gas contained in solution in the oil. Recovery by this method of so-called "solution gas drive" is allowed to continue until the energy of the solution gas is exhausted to such an extent that it will no longer cause substantial amounts of liquid to flow to the production wells. In the meantime, during this phase of production, free gas will separate from the liquid after the reservoir pressure drops below the original saturation pressure of the liquid, and as a result thereof

the reservoir will eventually reach a state that it has a substantial permeability to gas, so that both gas and liquid may flow therethrough as separate phases. When the reservoir has been so far depleted by solution gas drive that the economical limit of production by said method is being approached because reservoir energy has dropped so low that insufficient oil is flowing to the production wells, it is fairly common to provide a gas injection well, usually by converting one of the production wells, and to inject therethrough some gas, usually a hydrocarbon gas, at a pressure slightly in excess of the then existing reservoir pressure whereby to supply additional energy to the reservoir to sweep some of the remaining oil therefrom to the production wells. This method of production, which is commonly referred to as "gas sweep," differs from the method of the present invention in that the gas is injected only after the reservoir has become partially depleted, and furthermore in that it is carried out at a pressure of only about 1,500 p. s. i. which is considerably below the pressure required for the practice of the present invention, as will be explained in more detail hereinafter.

It is recognized that it has been proposed in the past to inject gas into oil reservoirs at pressures considerably above those which are employed in the conventional secondary gas sweep. However, such proposals, like the gas sweep method, are concerned with treating depleted reservoirs for the purpose of obtaining some of the oil which is left in reservoirs after they have been substantially completely depleted by earlier practiced conventional recovery methods. One such high pressure gas injection method is that disclosed in Patent No. 2,135,319 issued November 1, 1938, to George S. Bays. In his patent, Bays discloses a method of obtaining additional recovery from a depleted oil reservoir by passing injected hydrocarbon gases therethrough under pressures sufficiently high as to cause a retrograde evaporation into said gases of the lighter hydrocarbons present in the oil which was left behind in the reservoir at the conclusion of conventional recovery, and to carry said evaporated hydrocarbons along to the production well for production therefrom in the gaseous phase. Since the process described by Bays is one of evaporation only it is seen that the process is applicable only after the reservoir has a sufficiently high permeability to gas to permit the injected gases to pass freely therethrough, contacting only the surface of the remaining oil so as to evaporate therefrom some of the lighter hydrocarbons, and bring them to the surface in the gaseous phase.

It is seen, therefore, that the method of the present invention differs materially from both the conventional secondary gas sweep method and the high pressure evaporation method as typified by the Bays patent referred to above, since the present method contemplates injecting high pressure gases into a reservoir long before there has been any substantial depletion of the reservoir by conventional primary and secondary recovery methods and while the free gas content of the reservoir is low enough to insure that the unswept-out portion of the reservoir may be maintained substantially completely filled with the liquid phase to the substantial exclusion of a separate gas phase at the injection pressure.

Likewise, the method of the present invention is to be distinguished from the recycling of normally gaseous hydrocarbons incident to the operation of condensate reservoirs. It has long been the practice in producing from condensate formations to separate the normally gaseous components of the well fluid at the surface and to recompress a portion of the separated gases and return them to the formation, both as a conservation measure and in order to maintain the formation pressure at a level high enough to prevent retrograde condensation within the reservoir. It is obvious to one skilled in the art that the problems of producing from oil reservoirs are entirely foreign to those of producing from condensate reservoirs and therefore that the recycling of gases to a condensate reservoir is in no way related to increasing the production from oil reservoirs by injecting normally gaseous hydrocarbons thereinto.

One object of the present invention is to provide an improved method of producing oil from an oil reservoir which will insure a higher ultimate recovery of stock tank oil therefrom than can be obtained by the practice of heretofore known methods.

Another object of this invention is to provide a method of increasing the ultimate recovery of oil from oil reservoirs by injecting thereinto normally gaseous hydrocarbons at a pressure and rate sufficiently high to maintain the unswept-out portion of the reservoir substantially filled with reservoir oil in the liquid phase to the substantial exclusion of any separate gaseous phase.

It is a further object of this invention to provide a method whereby the ultimate recovery of oil from a reservoir containing undersaturated liquid oil may be increased by injecting into said reservoir normally gaseous hydrocarbons at a pressure and rate sufficiently high to maintain the pressure on said reservoir above the original saturation pressure of said reservoir oil.

It is a further object of this invention to provide a method of increasing the ultimate recovery of oil from producing reservoirs having a critical gas saturation which comprises increasing the pressure on said reservoir, by the injection of normally gaseous hydrocarbons, to an elevated pressure sufficient to cause the reservoir oil to absorb substantially all gas existing in the reservoir, and thereafter continuing to inject normally gaseous hydrocarbons into said reservoir at said elevated pressure.

A still further object of this invention is to provide a method of increasing the ultimate recovery of oil from oil reservoirs by injecting into the reservoir normally gaseous hydrocarbons to maintain the pressure thereon at or above the original saturation pressure of the reservoir oil, and thereafter continuing to inject into said reservoir normally gaseous hydrocarbons at a pressure and rate sufficient to maintain the reservoir at a pressure at least as great as said original saturation pressure.

It is a further object of this invention to provide a method of increasing the ultimate recovery of oil from a producing oil reservoir by injecting thereinto normally gaseous hydrocarbons thereby maintaining the pressure on the reservoir at a pressure between about 3,000 p. s. i. and 6,000 p. s. i. and also above the original saturation pressure of the reservoir oil.

Other objects and advantages of this invention will become apparent from the description and drawings which follow.

Figure 1 is a diagrammatic view showing a system for carrying out the present invention.

Figure 2 is a curve illustrating the relationship of the per cent recovery of original stock tank oil in place to the pressure maintained on a typical reservoir by the injection of normally gaseous hydrocarbons according to the method of this invention.

Figure 3 is a curve illustrating the relationship of the per cent recovery of original stock tank oil in place to the gas saturation existing in a reservoir at the time injection or normally gaseous hydrocarbons according to this invention is undertaken.

Briefly, this invention involves injecting normally gaseous hydrocarbons into a producing reservoir at a pressure and rate high enough to insure that the unswept-out portion of the reservoir will be maintained substantially filled with the liquid phase of reservoir oil, and preferably high enough to maintain the oil in the unswept-out portion of the reservoir undersaturated with gas so that it will absorb, and be swollen by, the injected gases coming into contact therewith. As explained hereinbefore, the term "producing reservoir" is used to refer to a reservoir which has not been so far depleted by conventional recovery methods that it has reached such a high free gas content that it cannot be reduced to below

the critical gas saturation by injecting into the reservoir normally gaseous hydrocarbons to increase the reservoir pressure to a value within the range contemplated for the practice of this invention.

In the practice of this invention it is essential that the pressure on the reservoir be maintained at all times high enough to insure that the free gas content of the unswept-out portion of the reservoir will not be at the critical gas saturation, as hereinbefore defined. Thus, the invention may be practiced by operating the reservoir at a pressure sufficient to maintain the oil in the uncontacted portion of the reservoir in an undersaturated state. The term "undersaturated" when used herein to refer to an oil or reservoir liquid means an oil or reservoir liquid hydrocarbon which does not have dissolved therein all the normally gaseous hydrocarbons which it can absorb under its existing conditions of temperature and pressure.

It will be appreciated, of course, that reservoir pressure obtained and maintained by the injection of normally gaseous hydrocarbons is not a function of injection pressure alone, but is also dependent upon the rate at which the gases are injected. Thus, although injection pressure must in any event be at least incrementally above existing reservoir pressure, if it is desired to increase reservoir pressure, the rate at which the gases are injected must be sufficiently above the rate at which fluid is being removed from the reservoir to insure that the total material in the reservoir is increasing, while if it is desired to merely maintain reservoir pressure at a selected level, the rate of injection need be great enough only to insure that a material balance is maintained between injected gas and withdrawn fluid.

As will appear hereinafter, the effect on the oil of the injected gases and the mechanics of flow of the oil and gas through the reservoir is different, depending upon whether the oil in the unswept-out portion of the reservoir is saturated or undersaturated. Therefore, to facilitate a clear understanding, the invention will first be described with respect to an operation in which the reservoir pressure is low enough that the oil in the unswept-out portion is saturated, but still high enough to prevent the existence of a critical gas saturation in the unswept-out portion. Thereafter, the invention will be described with respect to an operation in which the reservoir pressure is maintained sufficiently high to keep the oil in the unswept-out portion undersaturated.

In the first case, normally gaseous hydrocarbons which are injected into a reservoir through an injection well displace the oil in the vicinity of the injection well, forcing it to flow in the direction of production wells. However, in the process of this invention, the gas when injected at high pressures raises the reservoir pressure and most of the free gas existing in the unswept-out portion of the reservoir is pushed back into solution with the liquid oil making such portion of the reservoir almost void of any free gas. The unswept-out portion of the reservoir at this higher reservoir pressure is almost completely full of oil in the liquid phase, thus decreasing the opportunities for the injected gas to by-pass the liquid reservoir oil. Therefore, it is seen that the injected gases will be more efficient in displacing the oil from the reservoir when it is in this liquid state.

Because gaseous hydrocarbons are so much less viscous than oil, their efficiency as a displacing agent for oil is low even if there is no separate gaseous phase in the reservoir. However, hydrocarbon gases which are rich in hydrocarbon fractions in the range of C_2 through C_{15} (hereinafter referred to as "intermediates") have a much greater efficiency as a displacing agent for oil than do lean gases, that is, those which are mostly methane with small amounts of ethane. This, of course, is obvious from the fact that the viscosity of the gases in the intermediate range is higher than the viscosity of lean gases and hence the viscosity ratio between the displacing gas and the displaced liquid is improved.

On the other hand, it has been found that it is not necessary to inject rich gases into a reservoir in order to obtain the advantages of using rich gas as the displacing agent for the oil. It has been discovered that a lean gas injected into a producing oil reservoir which as a result is maintained at a reservoir pressure above about 3,000 p. s. i. will become enriched as it travels through the reservoir and will therefore become a rich gas by the time it reaches a gas-oil interface. The reason for this phenomenon is thought to be explained in the following manner. As the injected gas moves out into the reservoir in a direction away from the injection well it displaces a large proportion of the reservoir oil in the direction of the production wells, but inherently, some of the oil will be left behind in the swept-out portion of the reservoir. Now, as each new increment of the injected gas passes into the reservoir it comes in contact with the oil which was left behind and strips therefrom a portion of the intermediates, thus becoming enriched thereby. As each increment moves through the swept-out portion of the reservoir in the direction of the advancing gas front it becomes more and more enriched by the intermediates which it strips from the oil left behind the gas front. Thus, by the time any given increment of the injected gas has reached the zone of contact, that increment has been enriched and thus had its viscosity increased so that it acts more efficiently as a displacing agent for the oil than it would had it remained a lean gas. Of course, it will be obvious that the stripping action of the injected gas has the secondary effect of reducing the oil left in the reservoir behind the gas front by an amount equal to the volume of the intermediates stripped therefrom. Thus, by injecting the normally gaseous hydrocarbons above about 3,000 p. s. i. not only is the efficiency of the gas as a displacing agent increased so that less oil is left behind the advancing gas front, but also that oil which is left behind is still further reduced in amount by the stripping action of the injected gas. It is emphasized that the injected normally gaseous hydrocarbons do not exhibit this stripping action to any appreciable extent when injected at pressures below about 3,000 p. s i.

Thus, it is seen that by operating a reservoir at a pressure high enough to maintain the unswept-out portion substantially liquid filled, normally gaseous hydrocarbons injected thereinto will function more efficiently as a displacing agent for the oil than they would if the free gas content of the unswept-out portion was sufficiently high to permit any substantial by-passing. Furthermore, by maintaining the pressure on the reservoir above about 3,000 p. s. i. by injecting hydrocarbon gases at a high pressure, the injected normally gaseous lean hydrocarbon gas becomes enriched by stripping the intermediates from the oil left behind the advancing gas front which serves the dual function of improving the viscosity ratio at the gas-oil interface, and reducing the volume of the oil left in the reservoir behind the advancing gas front.

In the second case of producing oil according to the method of this invention, that is, the case in which the gas is injected at such a pressure that the pressure on the reservoir is maintained high enough to keep the oil in the unswept-out portion of the reservoir undersaturated, there are additional effects of the high pressure gas injection which are not present when the reservoir pressure is maintained low enough so that the oil in the unswept-out portion is saturated. The principal additional effect is that some of the injected gases will dissolve in the undersaturated liquid as they come in contact therewith, thus causing the liquid to swell or increase in volume. For convenience in discussing this phase of the invention the swelling effect which the injected gases have on the reservoir oil will be referred to as the "reservoir volume ratio" effect, as hereinbelow defined. When oil from a

reservoir is stabilized through one or more separators down to atmospheric pressure, those hydrocarbons which are gaseous at atmospheric pressure will separate, leaving a stabilized liquid which is commonly referred to as "stock tank oil." The ratio of the volume of reservoir oil (that is, before stabilization) to the volume of stock tank oil which is obtained by reducing the pressure on the reservoir oil to atmospheric is termed "formation volume factor." In the practice of the present phase of this invention the volume of the reservoir oil will be increased in the reservoir due to the dissolution therein of some of the injected hydrocarbons. The term "reservoir volume ratio" has been adopted, and will be used throughout this specification, to define the ratio of a volume of the reservoir oil after expansion due to the absorption of injected gases, to the volume of original stock tank oil which was present in the uncontacted reservoir oil. Thus, whereas "formation volume factor" is used to define the ratio of the volume of natural reservoir oil to the volume of stock tank oil contained therein, the term "reservoir volume ratio" is used to define the volume of reservoir oil which has been artificially swollen or expanded by injected gases to the volume of stock tank oil contained therein.

It is well known, of course, that if a hydrocarbon liquid which is undersaturated at a given pressure is brought into contact with a gaseous hydrocarbon at that same or higher pressure (temperature remaining constant) the liquid will dissolve a sufficient amount of the gas in order to become saturated (assuming sufficient gas is present), and will in the process of dissolving the gas become swollen or expanded in accordance with the amount of gas absorbed. It has been further found that when an undersaturated oil of a given composition is contacted with a gas which is rich in intermediates (hereinafter referred to as a "rich" gas), the undersaturated oil will, in the process of becoming saturated, absorb a much greater volume of this gas and consequently become much more swollen thereby than would be the case had the same undersaturated oil been brought in contact with a lean gas under the same conditions of pressure and temperature. Such being the case, it is seen that a given volume of oil which has been saturated with rich gas will contain less stock tank oil than the same volume of oil which has become saturated with lean gas, assuming that the original undersaturated oil in which the gases were dissolved was the same in both cases. Therefore, if a reservoir containing a given amount of undersaturated oil is contacted at a pressure above saturation pressure with a rich gas whereby to swell the reservoir oil, and if the reservoir is then depleted to a selected low liquid saturation, it will be seen that the amount of stock tank oil left in the reservoir after depletion will be less than would be the case if the contacting gases had been lean, because the reservoir volume ratio is greater in the former case than in the latter. It will also be appreciated that causing even a lean gas to be absorbed in the reservoir oil will result in leaving less stock tank oil in the depleted reservoir than if the original reservoir oil should be withdrawn from the reservoir in its original form.

The increase in reservoir volume ratio obtained when undersaturated oil is contacted with normally gaseous hydrocarbons at a pressure above the saturation pressure of said oil, as well as the increased effectiveness of contacting the undersaturated oil with rich gas instead of lean gas, may be demonstrated in the laboratory in the following manner. A known volume of undersaturated oil, which represents oil contained in the unswept-out portion of the reservoir, is placed in a container which is maintained at a pressure substantially above the saturation pressure of the oil. Normally gaseous hydrocarbons, such as gaseous mixtures containing methane with a minor amount of the lower molecular weight hydrocarbons are introduced into the container while maintaining the pressure substantially constant and the container

is agitated so as to aid the dissolution of the gas in the oil. The volume of gas introduced into the container should be in excess by a small amount of that required to saturate the oil. This excess gas is allowed to remain in contact with the saturated oil until equilibrium is reached. A second known volume of the same undersaturated reservoir oil is placed in a second container and the excess gas from the first container, which has become enriched by stripping some of the intermediates from the liquid in the first container while coming into equilibrium therewith, is introduced into the second container which is agitated so as to aid the solution of the gas and the oil. The volume of gas used is sufficient to just saturate the oil. Knowing the volume of stock tank oil contained in each of the two containers, the reservoir volume ratios may be determined from the expanded oil volume in such containers. It will be noted that there will be a substantial increase in reservoir volume ratio due to saturation of the liquid with the lean gas, but that there is a much greater increase in reservoir volume ratio when the rich gas is brought into contact with the undersaturated oil.

The following example is given for the purpose of illustration.

	Composition of Injected Gas, Mol Percent	Composition of Reservoir Oil, Mol Percent
C_1	81.4	38.16
C_2	17.60	11.54
C_3	1.00	10.30
C_4		6.65
C_5		4.31
C_6		3.98
C_{7+}		25.06
Total	100.00	100.00

With a lean gas of the above composition and with a pressure of 4,218 p. s. i. on the first container and a pressure of 3,910 p. s. i. on the second container, the reservoir volume ratio was found to increase from a value of 1.8 for the uncontacted oil to a value of 2.35 for the reservoir oil in the first container and to a value of 7.06 for the reservoir oil in the second container.

Thus it is seen that by maintaining the pressure on a reservoir high enough to keep the oil in the unswept-out portion thereof undersaturated it is possible to dissolve therein some portion of the injected gases whereby to increase the reservoir volume ratio thereof. The effect of increased reservoir volume ratio in reducing the amount of stock tank oil left in the reservoir after depletion has already been explained above. Additionally, it will be appreciated that the oil which has thus been swollen by the absorption of normally gaseous hydrocarbons will be much less viscous and hence offer less resistance to flow so that it will actually be possible to reduce the liquid saturation at abandonment below that which would be possible if the reservoir oil were removed from the reservoir in its original more viscous condition.

Also, by maintaining the pressure on the reservoir above about 3,000 p. s. i. the same effect which would be obtained by injecting a rich gas at lower pressure may be obtained with a lean gas since the lean gas will, in passing through the swept-out portion of the reservoir strip intermediates from the residual oil and thus become enriched thereby.

As explained above in connection with operating a reservoir at a pressure low enough to permit the oil in the unswept-out portion to remain saturated, there is a relatively favorable viscosity ratio established between the displacing gas and the displaced liquid when pressure on the reservoir is maintained above about 3,000 p. s. i. to enable the injected gas to become enriched before reaching the gas-oil interface. There is present an even greater viscosity ratio advantage when the reservoir is maintained

at a pressure sufficiently high to keep the oil in the unswept-out portion undersaturated so that it may absorb some of the injected gases as they move into the uncontacted zone. Thus, when the enriched normally gaseous hydrocarbons come in contact with, and are dissolved in, the undersaturated reservoir oil at the interface a considerably less viscous liquid oil phase results. As a result of this phenomenon there exists in the zone of contact a considerable amount of this less viscous liquid phase. The favorable ratio between the decreased liquid viscosity and the increased injected gas viscosity results in a relatively efficient displacement by the gas in this zone. In the extreme, if the pressure is high enough or if the oil is of suitable composition, the enriched gas and the undersaturated oil at the interface will be completely miscible and the resulting displacement will be extremely efficient as though a miscible liquid were "washing out" the reservoir.

It is thought that the production of oil from a reservoir in accordance with this phase of the invention, in which the oil in the unswept-out portion of the reservoir is maintained undersaturated, may be described as follows. Gas injected into the reservoir is absorbed by the undersaturated liquid which becomes swollen, and thus has its reservoir volume ratio increased, thereby. At the same time, pressure of the injected gases causes a portion of the reservoir oil to move away from the injection well in the direction of production wells. Since the injected gases are not 100% efficient in displacing the reservoir oil, a portion of the swollen oil will be left behind the advancing gas front. As each increment of additional gaseous hydrocarbon is injected into the reservoir, it will come in contact with the residual swollen oil left behind in the swept-out portion of the reservoir, stripping therefrom a portion of the intermediates whereby that increment of the gas will be enriched and the residual oil shrunk. As each increment of the gas which has become enriched reaches the zone of contact between the gas and oil it is in turn absorbed by oil at the interface whereby to increase the reservoir volume ratio of said oil. It is emphasized that the above theory of operation has been advanced merely to facilitate an understanding of the invention and that the invention is not to be considered as limited in any way to any specific theory of operation.

In the drawings, Figure 1 is a diagrammatic view showing a system which may be used for carrying out this invention. It will be understood, of course, that the same system may be used regardless of whether the reservoir is to be operated so as to maintain the reservoir oil saturated or undersaturated. In Figure 1, numeral **1** denotes generally the surface of the earth. Communicating with oil reservoir **2** are injection well **3** and production well **4**. These wells may be of a conventional type and each includes, for example, at least a casing string **5**, the interior of which is in communication with reservoir **2** through suitable perforations **6**, and a tubing string **7** disposed within the casing for conducting fluids to or from the reservoir.

Normally gaseous hydrocarbons, such as gaseous mixtures containing methane with minor amounts of the lower molecular hydrocarbons, are compressed to a desired pressure above 3,000 p. s. i. and necessarily above the existing reservoir pressure by a suitable compressor **8**, which may be of any conventional type, and are passed through valve controlled pipe **9** into injection well **3** from which the injection gas flows into the reservoir to contact the oil contained therein. Gas from a conventional oil field separator **10**, provided for stabilization of production flowing from reservoir **2** to the well surface through production well **4**, may be employed as the injection gas, the separator gas entering compressor **8** through flow pipe **11** and valve controlled line **12**. In practice, however, the volume of the separator gas frequently is inadequate, making it necessary to supplement it with gas obtained from a suitable external source, not shown, such as a gas well. If desired, the injection gas may consist solely of gas from the external source, which gas is conducted to compressor **8** through valve controlled line **13** and flow pipe **11**.

Simultaneously with the injection of gas into the reservoir, oil which is swept from the reservoir by the injected gas is removed to the surface of the earth through production well **4** without substantial lowering of the reservoir pressure. This oil produced through well **4** flows by means of valve controlled pipe **14** into separator **10**, operated at a pressure of, for example, 500 p. s. i. less than the pressure of the oil at the well head, wherein the oil is stabilized. As pointed out hereinabove, the separator gas, which comprises normally gaseous hydrocarbons, is conducted by means of lines **12** and **11** into compressor **8** and is compressed to the desired pressure for injection into the reservoir. The oil fraction from separator **10** flows through valve controlled pipe **15** into a second separator **16**, which preferably is operated at atmospheric pressure. Although the separator gas from separator **16** may be reinjected into the reservoir through well **3**, because of the relatively high cost involved in the repressuring thereof, it is preferable to employ such gas for other purposes, for example, as fuel for the operation of auxiliary field equipment. The oil is passed from separator **16** into a suitable storage tank **17** by means of valve controlled flow line **18**.

As above pointed out, when normally gaseous hydrocarbons are injected into an oil reservoir, in accordance with the invention, at a pressure in excess of about 3,000 p. s. i., there is an unexpected increase in the amount of oil that may be recovered over that recoverable by heretofore known methods of oil production, and therefore, a corresponding decrease in the residual oil in the reservoir. This has been demonstrated by laboratory experiments carried out on an artificial core under conditions simulating a subterranean oil reservoir. The artificial core was prepared by filling a 25-foot length of 2-inch metal tubing having an oil jacket with 140 to 270 mesh sand. A filter was provided at either end of the tubing to retain the sand therein. A 26 liter pressure vessel used for storing the reservoir oil to be displaced was connected by means of a pipe to one end of the simulated reservoir and a suitable pump was connected in the pipe for transferring to the reservoir high pressure fluids. The normally gaseous hydrocarbons to be injected into the simulated reservoir were stored in a high pressure vessel having capacity of about 30 liters and which preferably was connected by a suitable line to the same end of the reservoir as was the 26 liter storage cell hereinbefore mentioned. To the other end of the simulated reservoir a single pipe was connected for conducting effluent from the reservoir to a high pressure visual cell of conventional design. The function of the visual cell is to permit observation of the reservoir effluent whereby a determination may be made, if desired, of whether the effluent flowing from the reservoir at any instant is a liquid or gas or a mixture thereof. From the visual cell the reservoir effluent was conducted by means of a valve controlled pipe into a separator operated at atmospheric pressure wherein the effluent was stabilized. The stabilized liquid and the gaseous fraction from the atmospheric separator were metered to determine the volume thereof.

The laboratory experiments with the above described apparatus were conducted in the following manner. Oil which had been stabilized at atmospheric pressure, and which is referred to hereinafter as "dead" oil, was pumped into the simulated core or reservoir under a pressure of 500 p. s. i., for example, to displace air or gas or other fluid which was present. By circulating hot oil in the jacketed section of the apparatus the core was brought up to the desired reservoir temperature. The reservoir oil was then pumped into the core from the 26 liter storage vessel until all of the dead oil had been displaced and the core was at the desired reservoir pressure. At this

time injection of normally gaseous hydrocarbons was commenced by displacement of such gas from the 30 liter vessel with water. By maintaining the effluent end of the core at a pressure somewhat lower than the injection pressure, such, for example, about 50 p. s. i. lower, the injected gas was caused to flow through the core forcing oil therefrom. The oil passed through the visual cell and into the atmospheric separator wherein it was stabilized. Gas injection was continued until the gas-oil ratio of the effluent was equal to 30,000.

The following examples of results obtained in the laboratory by the experiments conducted as above described illustrate the oil recoveries obtained by means of the present method as compared with oil recovery by gas drive methods mentioned hereinbefore, i. e., by gas injection at pressures of the order of 1,500 p. s. i. or in any event less than about 3,000 p. s. i.

Example I

In this case the oil having an original saturation pressure of 2,780 was placed in the simulated reservoir at 2,900 p. s. i. and permitted to flow, by solution gas drive, until the pressure in the reservoir had dropped to 1,200 p. s. i. Thereafter, the normally gaseous hydrocarbons were injected into the reservoir and production continued until the gas-oil ratio of the effluent was 30,000. Because of the free gas content existing in the reservoir when the gases were injected, there was by-passing of the liquid by the injected gas, simulating oil production by conventional gas drive methods. Only 45% of the original oil in place was recovered by this method, which is not in accordance with the present invention. The injected gas and reservoir oil were of the following compositions:

	Composition of Injected Gas, Mol Percent	Composition of Reservoir Oil, Mol Percent
C_1	87.9	22.6
C_2	11.6	5.1
C_3	0.5	3.6
C_4		4.8
C_5		4.9
C_6		5.0
C_{7+} (Av. Mol. Wt. 200)		54.0
Total	100.0	100.0

Example II

Employing injected gas and reservoir oil of the compositions set forth below, the injected gas being of the same composition as that employed in Example I, a recovery of 65% of the oil in place was realized with an injection pressure of 2,900 p. s. i. This pressure, it is to be noted, is at the threshold of the pressures required for producing oil in accordance with the present invention. The reservoir oil had an original saturation pressure of 2,780 p. s. i., so the oil in the unswept-out portion of the reservoir was undersaturated, thus insuring that there was no separate gas phase in said portion of the reservoir to induce gas flow as a separate phase.

	Composition of Injected Gas, Mol Percent	Composition of Reservoir Oil, Mol Percent
C_1	87.9	44.8
C_2	11.6	13.0
C_3	0.5	9.5
C_4		6.3
C_5		3.1
C_6		3.8
C_{7+} (Av. Mol. Wt. 200)		19.5
Total	100.0	100.0

Example III

Employing the same injected gas and reservoir oil as that of Example II, and with an injection pressure of 4,000 p. s. i. 85% of the oil in place was recovered. It will be noted that in this case the injection pressure of 4,000 p. s. i. was considerably above the original saturation pressure (2,780 p. s. i.) of the reservoir oil so that there was considerable absorption of the injected gas by the reservoir oil resulting in an increase in reservoir volume ratio.

Example IV

Employing injected gas and reservoir oil of the compositions below set forth and with an injection pressure of 4,000 p. s. i. a recovery of 92% of the oil in place was realized. In this case, it is seen that there is a definite advantage in having a rich gas displace the reservoir oil, since Examples III and IV are identical except for the composition of the injected gas. However, it is noted that, in the case of an actual reservoir, where the injected gas must travel a great distance through the reservoir in reaching the gas-oil interface, the advantage of injecting an initially righ gas will virtually disappear because lean gas will become sufficiently enriched by stripping intermediates from the residual oil over which it passes in reaching the interface.

	Composition of Injected Gas, Mol Percent	Composition of Reservoir Oil, Mol Percent
C_1	72.4	44.8
C_2	16.4	13.0
C_3	8.0	9.5
C_4	2.2	6.3
C_5	0.6	3.1
C_6	0.1	3.8
C_{7+} (Av. Mol. Wt. 200)	0.3	19.5
Total	100.0	100.0

The examples given above serve to illustrate that an unexpected increase in the recovery of oil may be obtained by this novel method of oil production wherein the unswept-out portion of the reservoir is maintained liquid-filled, and normally gaseous hydrocarbons are injected into the reservoir at a pressure above about 3,000 p. s. i.

Figure 2 is a curve illustrating the per cent of original oil which is recoverable as a function of the operating pressure in a typical reservoir having therein oil with an original saturation pressure of about 2,800 p. s. i. For pressures below about 3,000 p. s. i. it will be noted that there is only a slight increase in recovery obtainable by increasing the pressure. Beginning at about 3,000 p. s. i., however, it is noted that increased pressure results in an unexpectedly large percentage increase in oil recovered. It will be further noted that the curve levels off again for pressures above about 4,000 p. s. i., indicating that no substantial part of the oil which is not recoverable by operating the reservoir at about 4,000 p. s. i. may be recovered by operating above that pressure. Therefore, while there is no theoretical upper limit to the pressure maintained on reservoirs into which gases are injected in accordance with this invention, there is an economic limit of around 4,000 p. s. i. when displacing oil with an original saturation pressure of about 2,800 p. s. i. since operating at a higher pressure does not result in the recovery of a substantially greater amount of the original oil in place. It is to be understood that the curve shown in Figure 2 is merely illustrative of the relationship of recovery to injection pressure and that deviations may result depending upon the composition and original saturation pressure of the reservoir oil. However, such deviations will not affect the general shape of the curve which is illustrative of most, if not all, naturally occurring oil reservoirs. So far as any presently known reservoirs are concerned, there does not appear to be any advantage in maintaining a pressure above about 6,000 p. s. i., therefore, the

preferable pressure range for operating reservoirs in accordance with this invention is between about 3,000 and about 6,000 p. s. i. which pressure must also, of course, be at least equal to the original saturation pressure of the oil in the reservoir. It will be appreciated by those skilled in the art that care must be taken in any event to prevent increasing the reservoir pressure to a level which might result in lifting the overburden or otherwise damaging the reservoid by causing heaving or cracking.

It was pointed out earlier that the method of this invention is preferably applied to a reservoir the pressure of which has not dropped below the original saturation pressure of the reservoir oil. However, as has been pointed out, the method is applicable to any reservoir in which the free gas content is low enough that the oil in the unswept-out portion of the reservoir may, upon having the pressure thereon increased sufficiently, take back into solution the free gas which separated therefrom after the pressure dropped below the original saturation pressure. Figure 3 is a curve illustrating the per cent of original oil recoverable as a function of the gas saturation existing in a reservoir at the time of increasing the pressure thereon and recovering oil therefrom in accordance with the method of this invention. It will be noted from this curve that ultimate recovery will decrease as the free gas content prior to initiating operation in accordance with this invention is allowed to increase. The curve thus illustrates the importance of beginning the injection of normally gaseous hydrocarbons in accordance with the method of this invention early in the life of a reservoir and before any substantial gas saturation has been permitted to develop.

It is to be understood that the invention is applicable to high pressure oil reservoirs whether in the virgin state or after a period of production, provided, however, that the reservoir has not been depleted to the extent that injected gas would by-pass the oil and thereby effect recovery merely by evaporation into the injected gas and subsequent recovery from the gas by retrograde condensation at the surface. Moreover, whereas in most cases the normally gaseous hydrocarbons will be injected into the reservoir at substantially the existing reservoir pressure, in some cases it may be desirable to inject the gas at a pressure of 1,000 p. s. i. or more in excess of the existing reservoir pressure. This is particularly true of virgin reservoirs having relatively low initial pressures and also of reservoirs which have been produced until their pressure has fallen below 3,000 p. s. i. This invention in its broadest aspect is applicable to either saturated or undersaturated oil reservoirs if such reservoirs have a free gas content below the critical gas saturation at the injection pressure. In its narrower aspect this invention is applicable to undersaturated oil reservoirs rather than saturated reservoirs. As pointed out previously, when a normally gaseous hydrocarbon is injected into a reservoir containing undersaturated liquid reservoir oil, some of the gas will dissolve into the reservoir oil and some of the reservoir oil will be stripped by the gas. The zone of contact between the swept-out and unswept-out portions of the reservoir in this case will therefore be composed of expanded reservoir oil and enriched gas. Therefore, the zone of contact will contain fluids which are more similar to the reservoir oil and the injected gas. This similarity between the zone of contact and the reservoir oil and between the zone of contact and the injected gas results in a relatively efficient displacement by the gas.

In a saturated reservoir, the above described exchange of higher and lower molecular weight hydrocarbons does not take place. As stated previously, the gas merely strips some of the intermediate molecular weight hydrocarbons from the liquid reservoir oil. In a few cases involving saturated reservoirs having a low free gas content, an increase in the reservoir pressure will push the free gas back into solution with the reservoir oil making the reservoir oil undersaturated. In these cases, the hydrocarbon exchange previously referred to does take place and a relatively efficient displacement of the oil will result. However, this operation in a saturated reservoir whose unswept-out portion is made undersaturated by raising its pressure gives a somewhat lower recovery than may be realized from oil reservoirs which at the beginning of the gas injection are undersaturated. As evidenced by Figure 3, if the free gas content of the reservoir is allowed to become too great, the ultimate recovery by the displacement from the reservoir is much lower. By the term "undersaturated oil reservoir," as used herein, is meant any subterranean reservoir containing oil which does not have dissolved therein all of the normally gaseous hydrocarbons possible at the temperature and pressure of such reservoir. By contrast, a saturated oil reservoir is a subterranean reservoir containing oil which has dissolved therein all of the normally gaseous hydrocarbons possible at the temperature and pressure of such reservoir.

While in the foregoing there have been shown and described preferred embodiments of this invention, it is to be understood that minor changes in the details of construction, combination, and arrangement of parts may be resorted to without departing from the spirit and scope of the invention as claimed. For example, whereas only a single injection and production well are shown, two or more of such wells may be utilized if desired.

We claim:

1. The method of recovering oil from a reservoir containing hydrocarbons in the liquid oil phase but having substantially no separate gaseous phase such liquid oil being undersaturated with hydrocarbon gases and thereby being capable of absorbing normally gaseous hydrocarbons, said reservoir having in communication therewith at least one injection well and one production well, comprising the steps of injecting into the reservoir through said injection well normally gaseous hydrocarbons at a predetermined pressure whereby said injected gases will initially contact a portion of the reservoir oil adjacent the injection well and will be absorbed by such portion of the reservoir oil to establish a zone of contact which advances from said injection well in the direction of the production well while the injection of said normally gaseous hydrocarbons is continued, said predetermined pressure being great enough to maintain on said reservoir a pressure within the pressure range of 3000 to 6000 p. s. i. and which also is at least greater than the original saturation pressure of the liquid oil such that the portion of the reservoir ahead of the advancing zone of contact will be maintained substantially filled with the liquid oil phase to the exclusion of any separate gaseous phase, and simultaneously withdrawing from the production well the reservoir oil in the liquid phase.

2. The method of recovering oil from a reservoir containing hydrocarbons in the liquid oil phase and a small volume of light-weight hydrocarbons as a separate free gaseous phase, and wherein the oil phase and the gaseous phase are under a pressure which is approximately equal to or slightly lower than the original reservoir saturation pressure, said reservoir having in communication therewith at least one injection well and one production well, comprising the steps of injecting into the reservoir through said injection well normally gaseous hydrocarbons at a predetermined pressure whereby said gases will build up the reservoir pressure, thereby causing said hydrocarbons in the free gaseous phase to be pushed back into solution with said liquid oil, making the reservoir oil undersaturated, continuing the injection of said gas into said reservoir at said predetermined pressure, whereby said injected gases will first be absorbed by that portion of the newly established undersaturated oil contained thereby to establish a zone of contact which advances from said injection well in the direction of the production well as the

injection of said normally gaseous hydrocarbons is continued, said predetermined pressure being great enough to maintain on said reservoir a pressure within the pressure range of 3000 to 6000 p. s. i. and which also is at least greater than the original saturation pressure of the liquid oil such that the portion of the reservoir ahead of the advancing zone of contact will be maintained substantially filled with the liquid oil phase to the exclusion of any separate gaseous phase, and simultaneously withdrawing from the production well the reservoir oil in the liquid phase.

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