This invention relates to the so-called secondary recovery of oil, i.e., the recovery of oil from partially depleted oil reservoirs. More particularly it relates to secondary recovery of oil through the use of the retrograde condensation phenomenon.

It is well known that the ordinary methods of primary oil recovery, i.e., flowing and pumping, remove only a small fraction of the total oil in place. Frequently as much as two-thirds of the original oil in the reservoir cannot be recovered even if pumping is carried to the point where a fairly high vacuum is maintained on the reservoir for a prolonged period.

Because of this fact considerable attention has been paid to the possibility of secondary recovery of oil from partially depleted formations. The common methods of secondary recovery are water flooding and gas repressuring. Both gas drive and water drive methods to be efficient must be practiced through the utilization of a large number of wells closely spaced. This is because they operate by moving the oil in the form of a gas–oil froth through the sand and such movements cannot be accomplished with reasonable pressure differentials and at reasonable rates when the distances involved are at all great. Since the cost of a well increases very rapidly with increasing depth, gas drive and water drive methods become economically unfeasible for deep reservoirs and the depth at which these methods can be used economically depends, of course, on various factors, notable among which is the price of oil at the time the operation is contemplated.

Mining methods, which have also been used as a means of secondary recovery, likewise increase in cost very rapidly as the depth of the reservoir increases and such methods can be used only in the case of very shallow oil-bearing formations and under very favorable crude oil price conditions.

One object of my invention is to provide an efficient and inexpensive method of secondary recovery of depleted oil reservoirs which can be used in the case of deep reservoirs. Another object of my invention is to provide a method of secondary recovery which can efficiently utilize widely spaced rather than closely spaced wells.

A still further object of my invention is to provide a secondary recovery method which will selectively recover the lighter and more valuable normally liquid hydrocarbons along with propane and butane. An additional object of my invention is to provide a novel secondary recovery method in which the oil components are moved in vapor rather than liquid or froth form. Further and more detailed objects of my invention will become apparent as the description thereof proceeds.

In dealing with a mixture of hydrocarbons in the vapor phase it is true in general that as the pressure is increased from zero upwards at a given temperature, a point is reached at which the heavier hydrocarbons begin to condense out in the liquid phase. Furthermore, as the pressure increase is continued the amount of condensation likewise increases. However, a peculiar phenomenon has been observed at high pressures and within certain temperature ranges. As the pressure is increased a point is ultimately reached at which no further condensation occurs and beyond which liquid actually tends to vaporize, thus reducing the amount of liquid phase present. This phenomenon is known as retrograde condensation or sometimes as retrograde vaporization.

The pressure at which the amount of liquid phase begins to decrease is referred to hereinafter as the critical retrograde condensation pressure. This pressure depends, of course, on the composition of the hydrocarbon mixture used and also on the temperature at which the system is maintained. For example, if the pressure is increased upon a gas and oil body, condensation of, say, hexane will occur up to a given point, possibly in the neighborhood of about 100° F. When the pressure is increased beyond this point, a retrograde condensation effect takes place and the hexane in the oil body commences to re-enter the vapor phase.

My invention utilizes this phenomenon in the secondary recovery of oil from partially depleted oil sand. In practicing my invention a hydrocarbon gas, preferably natural gas, is injected into the depleted reservoir under high pressure through one or more wells which need not be closely spaced—for instance, spacing as high as one injection well per 160 acres can be used. The pressure ultimately reached must exceed the critical retrograde condensation pressure by a substantial margin, at least 500 lbs./sq. in., and preferably at least 1,000 lbs./sq. in. The pressure used can be as high as desired, the main limiting factor being the cost of producing and maintaining excessive pressures. In general I prefer to raise the pressure in the reservoir to a value between about 1,500 lbs./sq. in., and about
8,000 lbs./sq. in. and preferably between about 2,500 lbs./sq. in. and about 5,000 lbs./sq. in. The gas is allowed to remain in contact with the oil in the depleted reservoir at this pressure for a period of at least several days and preferably several months to permit approximate equilibrium to take place within the very fine pores and capillaries of the reservoir. This period has been allowed in order to achieve approximate equilibrium, gas is produced from the formation. This gas may be produced from the same wells through which it is introduced and this constitutes an additional advantage over, and distinction from, gas drive and water drive methods which necessarily use separate wells for the driving fluid and the oil produced.

The gas is produced at as near reservoir pressure as practicable. In any event the pressure in the formation surrounding the well or wells from which the gas is produced is not allowed to drop below 1,500 lbs./sq. in. and preferably not below about 2,500 lbs./sq. in. It is also desirable that the pressure within the well itself be maintained above these pressures but this is not always essential since condensation within the well results in entrainment and the liquid thus separating out is not necessarily lost as it would be if the condensation occurred within the underground formation.

Due to the retrograde condensation phenomenon, or what is sometimes referred to as retrograde vaporization, the gas produced under high pressure contains normally liquid hydrocarbons from the underground formation which were dissolved in the gas by virtue of the high pressure. These hydrocarbons can be separated from the gas by merely lowering the pressure to some value in the neighborhood of the critical retrograde condensation pressure, for instance a pressure of from about 400 lbs./sq. in. to about 1,200 lbs./sq. in. and preferably from about 600 lbs./sq. in. to about 1,000 lbs./sq. in., and then separating the vapor and liquid phases. If the pressure is lowered below the critical retrograde condensation pressure, the liquid phase commences to enter the vapor phase which is, of course, undesirable since the objective is to separate the maximum amount of liquid hydrocarbons.

The pressure at which the liquid and vapor phases are separated should be at least about 500 lbs./sq. in. and preferably at least about 1,000 lbs./sq. in. below the minimum pressure within the reservoir. As previously indicated, at least a part of this pressure drop can occur within the well but the bulk of it preferably occurs above ground.

While it is possible, as above mentioned, to use the same well for the introduction and withdrawal of gas in accordance with my invention, this necessitates discontinuous operation, and it is greatly preferable to use different wells. Since, in practicing my invention the fluid leaving the formation is homogeneous and at least substantially free from any separate liquid phase, the point of gas injection can be either higher or lower on the reservoir than the point of withdrawal.

A simplified and highly diagrammatic illustration of one type of equipment for practicing my invention is shown in the accompanying drawing which forms a part of this specification, and is to be read in connection therewith. My invention will be further described with particular reference to the drawing.

A gas is introduced at high pressure into well "A", passes through the partially depleted oil reservoir 10, which is isolated by impervious strata 11 and 12, and by brine barrier 13, passes into well "B" at high pressure, is withdrawn from well "B" through line 14, and has its pressure reduced to form a liquid phase by virtue of the retrograde condensation effect. This liquid phase is removed by means of separator 15, the gas is recompressed and then re-introduced into well "A".

The gas introduced into well "A" can be composed in whole or in part of re-cycle gas withdrawn through well "B" as we have just seen, or all or part of it can come from a separate source, for instance, valve line 28. In any event, an extraneous gas is usually necessary for make-up purposes, since there is inevitably some slight loss. The gas introduced is constituted wholly or at least predominantly of one or more hydrocarbons having one or two carbon atoms per molecule. Usually methane is the main constituent, but ethane can be used. Natural gas, or other mixtures of methane and ethane, with or without minor quantities of heavier hydrocarbons, are the most suitable and available materials for use in practicing my invention.

This gas can be introduced at any pressure above about 1,500-2,500 lbs./sq. in., but substantially higher pressures are desirable to make the pressure drop for these figures represent the minimum pressures which should be built up within the reservoir.

As previously indicated the gas picks up heavier hydrocarbons (largely propane to heptane) from the otherwise unproductive oil films existing within the partially depleted oil reservoir 10, and then issues through well "B" and line 14. The pressure is reduced by means of pressure reduction valve 18 to a value in the neighborhood of the critical retrograde condensation pressure or in other words, to a pressure of from about 400 lbs./sq. in. to about 2,000 lbs./sq. in., and preferably from about 600 lbs./sq. in. to about 1,000 lbs./sq. in.

This pressure reduction is, of course, accompanied by a temperature reduction and this temperature drop causes further amounts of liquid phase to separate. In fact, further cooling by external means is desirable to gain still further liquid phase precipitation and still higher recoveries of hydrocarbons from propane to heptane and heavier. The temperature at which the liquid phase is separated and removed may suitably be from about 25° F. to about 150° F. Temperature adjustment is obtained by means of cooler 17 which may precede or follow pressure reduction valve 18, but preferably precedes it since cooling medium of higher temperature can then be used.

As a matter of fact, heavier hydrocarbons picked up by virtue of the retrograde condensation effect can be precipitated by cooling, without pressure reduction, and while this does not give as high recoveries as are obtained with pressure drops, recompression costs are reduced which compensates for the low recoveries to some extent.

Following pressure and/or temperature adjustment, the fluids enter separator 15, which may be of any conventional type. From this separator the liquid phase, separated by virtue of the retrograde condensation phenomenon is removed through valve 18, which is responsive to liquid level control 19, and then passes through line 20 to storage, or to a fractionation system, or a trap 75.
system of stage separation for removal of methane and ethane which can be recycled. Gas, stripped of a major portion of its components heavier than methane and ethane, is compressed 25 to about 2,500 lbs./sq. in. to about 5,000 lbs./sq. in. maintaining said gas in contact with the oil in said reservoir under pressure of this same order of magnitude for a substantial period of time, causing said gas to pass from said reservoir into a well while maintained at a pressure in excess of about 2,500 lbs./sq. in., lowering the pressure on said last-mentioned gas by at least about 1,000 lbs./sq. in. to a value within the range from about 600 lbs./sq. in. to about 1,000 lbs./sq. in. to separate liquid hydrocarbons by virtue of the retrograde condensation effect and removing the separated liquid hydrocarbons from the remaining gas.

5. A method of recovering oil components from a partially depleted underground oil reservoir which comprises introducing gas rich in methane into the said reservoir at a pressure in excess of about 1,500 lbs./sq. in. to about 5,000 lbs./sq. in., maintaining said gas in contact with the oil in said reservoir under pressures of this same order of magnitude for a substantial period of time, causing said gas to pass from said reservoir into a well while maintained at a pressure in excess of about 1,500 lbs./sq. in., issuing said gas from said second well lowering the pressure on said gas by at least about 500 lbs./sq. in. to a value within the range from about 400 lbs./sq. in. to about 1,200 lbs./sq. in. to separate liquid hydrocarbons by virtue of the retrograde condensation effect and removing the separated liquid hydrocarbons from the remaining gas.

6. A method of recovering oil components from a partially depleted underground oil reservoir which comprises introducing gas into the said reservoir at a pressure in excess of about 1,500 lbs./sq. in., maintaining said gas in contact with the oil in said reservoir under pressures of this same order of magnitude for a substantial period of time, causing said gas to pass from said reservoir into a well while maintained at a pressure in excess of about 1,500 lbs./sq. in., lowering the pressure on said last-mentioned gas by at least about 500 lbs./sq. in. to a value within the range from about 400 lbs./sq. in. to about 1,200 lbs./sq. in. to separate liquid hydrocarbons by virtue of the retrograde condensation effect and removing the separated liquid hydrocarbons from the remaining gas.
a second well while maintained at a pressure in excess of about 1,500 lbs./sq. in., recovering at least a substantial part of said heavier hydrocarbons, recompressing at least a substantial part of the remaining gas and recycling said recompressed gas while maintaining at a pressure in excess of about 1,500 lbs./sq. in., passing said recompressed gas together with dissolved heavier hydrocarbons picked up from said reservoir into a second well while maintained at a pressure in excess of about 2,500 lbs./sq. in., passing said gas to said reservoir. 10. A method of recovering oil components from a partially depleted underground oil reservoir which comprises introducing natural gas into said reservoir through a first well at a pressure of from about 1,500 lbs./sq. in. to about 8,000 lbs./sq. in., passing said gas through said reservoir while maintaining its pressure above about 1,500 lbs./sq. in., passing said gas together with dissolved heavier hydrocarbons picked up from said reservoir into a second well while maintained at a pressure in excess of about 2,500 lbs./sq. in., passing said gas to a value within the range from about 400 lbs./sq. in. to about 1,200 lbs./sq. in. to separate liquid hydrocarbons by virtue of the retrograde condensation effect, removing the separated liquid hydrocarbons from the remaining gas, recompressing at least a substantial part of said remaining gas to a pressure in excess of the reservoir pressure, and recycling said recompressed gas to said reservoir.

11. A method of recovering oil components from a partially depleted underground oil reservoir which comprises introducing natural gas into said reservoir through a first well at a pressure of from about 2,500 lbs./sq. in. to about 5,000 lbs./sq. in., passing said gas through said reservoir while maintaining its pressure above about 2,500 lbs./sq. in., passing said gas together with dissolved heavier hydrocarbons picked up from said reservoir into a second well while maintained at a pressure in excess of about 2,500 lbs./sq. in., passing said gas through said reservoir while maintaining its pressure above about 1,500 lbs./sq. in., passing said gas to a value within the range from about 400 lbs./sq. in. to about 1,200 lbs./sq. in. to separate liquid hydrocarbons by virtue of the retrograde condensation effect, removing the separated liquid hydrocarbons from the remaining gas, recompressing at least a substantial part of said remaining gas to a pressure of from about 2,500 lbs./sq. in. to about 5,000 lbs./sq. in., and recycling at least a substantial part of said recompressed gas to said reservoir.

12. A method of recovering oil components from a partially depleted underground oil reservoir which comprises introducing gas composed at least predominantly of at least one hydrocarbon having less than three carbon atoms per molecule into said reservoir through a first well at a pressure of from about 2,500 lbs./sq. in. to about 5,000 lbs./sq. in., passing said gas through said reservoir while maintaining its pressure above about 1,500 lbs./sq. in., passing said gas together with dissolved heavier hydrocarbons picked up from said reservoir into a second well while maintained at a pressure in excess of about 2,500 lbs./sq. in., passing said gas to a value within the range from about 400 lbs./sq. in. to about 1,200 lbs./sq. in., and recycling at least a substantial part of said recompressed gas to said reservoir.