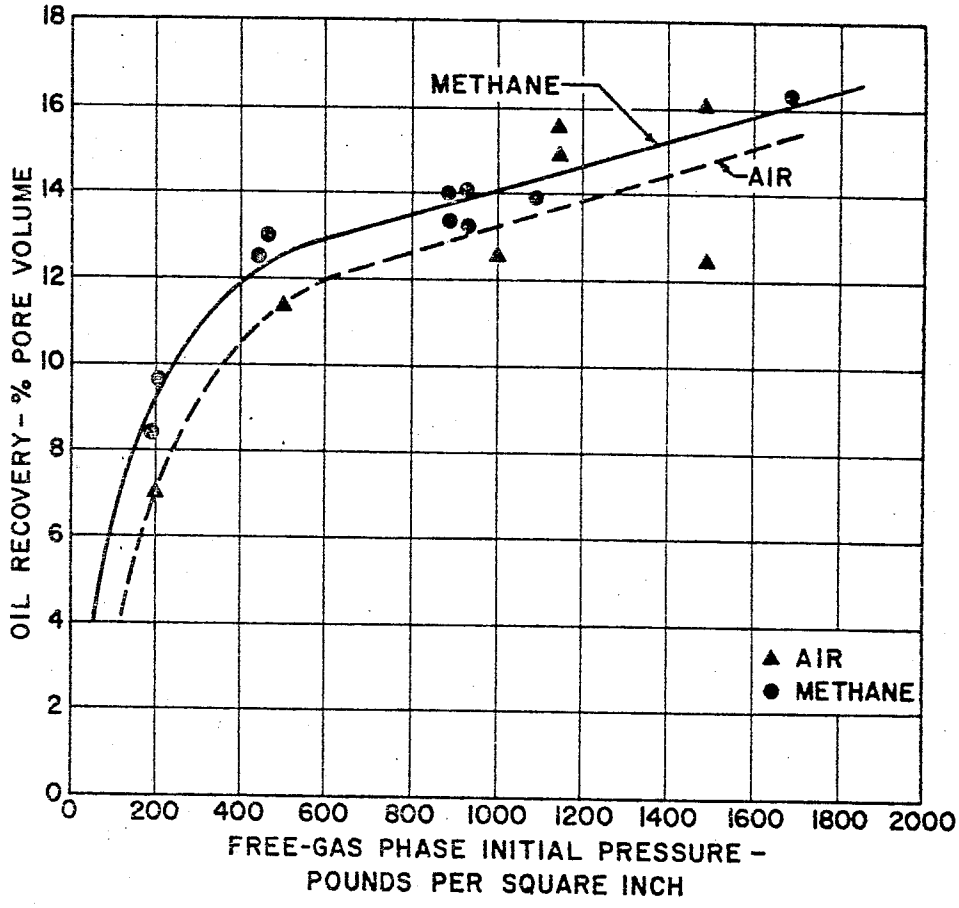
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RECOVERY OF OIL FROM WATERED-OUT RESERVOIRS

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RECOVERY OF OIL FROM WATERED-OUT RESERVOIRS

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The present invention relates to methods for the recovery of oil from subsurface reservoirs and more particularly relates to an improved process for recovering additional oil from previously exploited, watered-out reservoirs. In still greater particularity, the invention relates to a process for augmenting recovery from a watered-out reservoir by first establishing a high pressure free gas phase in the reservoir and thereafter reducing the pressure on the reservoir.

Experience has shown that techniques utilized in the primary exploitation of subterranean oil-bearing reservoirs generally permit the recovery of only a small fraction of the total oil initially present in such reservoirs. In order to stimulate further production after the natural reservoir energy has largely been expended by primary recovery techniques, a number of secondary recovery processes have been developed. The most widely used of these is the waterflooding process. By simply injecting water into an underground oil reservoir through one or more injection wells and forcing it in the direction of production wells spaced some distance from the injection wells, oil not recoverable by primary recovery techniques can be produced. An oil reservoir where injected water or natural water encroachment has reduced the oil saturation to a limit near the residual oil saturation characteristic of the displacement of oil by water in that particular reservoir is generally referred to as a "watered-out" reservoir. The waterflooding process is considerably more attractive than many other secondary recovery processes because the water utilized can ordinarily be obtained at little cost and need not be recovered from the reservoir in order to make the process economically feasible.

Waterflooding processes are generally carried out until a high ratio of water to oil at the production well makes further exploitation unattractive from an economics standpoint. Studies based in part upon the fluid content of cores taken from watered-out reservoirs indicate that from 20 to about 40 percent of the oil initially present may remain in a reservoir at the conclusion of a successful waterflooding project. There are thus many watered-out reservoirs which contain large quantities of potentially recoverable oil. Efforts to produce this oil, however, have largely been unsuccessful. Solvent displacement processes and other methods which might permit additional recovery from watered-out reservoirs are generally too expensive to warrant their use in such reservoirs. Less costly processes, those based upon the use of air or a similar gaseous displacing agent for example, are normally less efficient than waterflooding and hence are not effective in watered-out reservoirs. For this reason, tertiary recovery from waterflooded reservoirs has not been viewed favorably in the past.

The present invention provides a new and improved process for the recovery of oil from watered-out reservoirs which is considerably more attractive from the economics standpoint than processes advocated in the past. In accordance with the invention, it has now been found that appreciable quantities of oil can be recovered from an oil-bearing reservoir following waterflooding by establishing a high pressure free gas phase in the reservoir and thereafter reducing the reservoir pressure to produce the oil contained therein. The expression "free-gas phase"

as used herein refers to gas not dissolved in liquids present in the system. The use of this process generally permits the recovery of from about 30 to about 50 percent of the oil remaining in the affected portion of the reservoir after waterflooding and, where repeated pressuring and pressure reduction steps are utilized, may permit even more significant results. The cost of the process is low and hence it can be applied to many reservoirs from which additional oil cannot be economically recovered by any other known method.

The process of the invention is normally carried out in a watered-out reservoir containing one or more injection wells and one or more production wells spaced at some distance from the injection wells. Gas is injected into the injection wells in quantities and at a pressure sufficient to establish the necessary free gas phase. In most reservoirs, particularly those in which a water drive contributed to primary recovery, the production wells may be closed off prior to the introduction of gas at the injection wells. In some small reservoirs, however, it may be preferable to withdraw fluids from the production wells during the establishment of the free-gas phase. During an operation of the latter type, the production wells may be subjected to a suitable back pressure while gas is being introduced at the injection well or may instead be allowed to flow free initially and may thereafter be closed off as additional gas is injected to build up the reservoir pressure to the desired level. Following the establishment of the high pressure free-gas phase in this manner, the injection wells are closed off and the production wells are allowed to flow. If desired, back pressure may be maintained at the production wells and gradually reduced to control the flow. Substantial quantities of oil, together with gas and water, flow into the production wells and are produced. After substantially no more oil can be recovered from the production wells or the production rate has declined to an undesirably low level, the process may be repeated by reestablishing the high pressure free-gas phase and again reducing the reservoir pressure.

The process of the invention may also be utilized in single well operations. In this type of operation, gas is injected into the reservoir through the single well in quantities and at a pressure sufficient to establish the requisite free-gas phase. Thereafter, gas injection is halted and the well is permitted to flow. Oil, gas and water are produced until the oil production rate declines to an uneconomical level. Thereafter, gas may again be injected into the reservoir and the cycle repeated.

A number of gases may be employed in carrying out the process of the invention, the principal requirement for the gas selected being that it not condense under reservoir conditions of temperature and pressure. Gases which may be utilized include air, natural gas, flue gases, exhaust gases from internal combustion engines and similar gases available at low cost. Air and natural gas are preferred because of their ready availability and will be employed most frequently in practicing the invention.

The pressure of the free-gas phase established in the reservoir will generally range from about 100 pounds per square inch to about 3,000 pounds per square inch. It has been found that the quantity of oil recovered in the process of the invention increases with increasing pressure but that the greater recovery realized at extremely high pressures generally does not warrant the higher compression costs incurred. For this reason, it is generally preferred to employ gas pressures ranging from about 400 to about 1,500 pounds per square inch. The pressure utilized will, of course, depend upon the pressure in the reservoir at the onset of the operation. Sufficient pressure to permit injection of the gas must be used and hence higher gas pressures may be utilized in

high pressure reservoirs than would otherwise normally be used.

The amount of gas injected into the reservoir to establish the free-gas phase will generally range between about one percent and about twenty-five percent of the reservoir pore volume, determined at the reservoir temperature and the pressure of the free-gas phase to be established in the reservoir. The injection of gas in excess of about twenty-five percent of the reservoir pore volume has little or no effect upon the oil recovery obtained and in many cases may increase the cost of the operation to the point where it becomes economically unattractive. The use of from about 1 percent to about 15 percent of gas, based upon reservoir pore volume, is preferable in most instances.

The exact nature and objects of the process of the invention can best be understood by considering the results obtained in experimental work during which oil was recovered from watered-out cores by first establishing high pressure, free-gas phases in the cores and thereafter reducing the pressure. The attached drawing which shows the relationship between the initial pressure of the free-gas phase established and the oil recovered upon reduction of the pressure further illustrates the invention.

EXAMPLE I

In the first of a series of experiments, a 13-inch core of Weiler sandstone measuring 2 inches in diameter was prepared by placing it in a section of pipe and using a low melting metal alloy which expands upon cooling to seal it in place. The pipe was provided with an inlet and a longitudinally opposed outlet for injecting and withdrawings fluids. The core was then saturated with about 65 volume percent oil and about 35 volume percent connate water. In this initial test, crude oil obtained from the Loudon field in Illinois was used. The saturated core was thereafter flushed with water until all of the oil displaceable by water had been recovered from it. The oil content of the core was then determined. It was found that the waterflooding reduced the oil content of the core to 24.3% of the pore volume.

Following the waterflooding as described above, methane was injected into one end of the watered-out core at a pressure of about 1100 pounds per square inch. About 12 percent methane, based on core pore volume and measured at ambient temperature and the selected pressure was used. The fluids displaced by the injected gas were recovered at the opposite end of the core and analyzed. It was found that thus driving gas through the watered-out core displaced very little of the oil contained in the core, only about 0.1 percent of a pore volume.

After a high pressure, free gas phase had been established in the core as described above, the pressure upon the core was reduced and the fluids produced with the escaping gas were collected and analyzed. A significant quantity of oil, about 9.5 percent of the pore volume, was recovered from the core during this pressure reduction step. The final oil content of the core was 14.7 percent of the pore volume. This represents a forty percent reduction in the oil content of the core following waterflooding.

Following the initial test described above, additional tests were carried out in similar manner using air, nitrogen, flue gas and methane. Gas pressures were varied between about 200 pounds per square inch and about 1630 pounds per square inch. Tests were carried out with "Soltrol," a refined white oil having a viscosity of 1.4 centipoises, as well as with the Loudon crude oil. A 45-inch Weiler sandstone core was employed in some of the tests. The amount of gas injected ranged from 9 to 16 percent of the pore volume. The results obtained in this first series of experiments are set forth in Table I below.

Table I

EFFECT OF GAS COMPOSITION ON OIL RECOVERY FROM WATERED-OUT CORES

Run	Oil	Gas	Gas Pressure, p.s.i.	Gas Injected, Percent Pore Volume	Oil Content After Waterflood, Percent Pore Volume	Oil Content After Gas Drive, Percent Pore Volume	Oil Recovered by Gas Drive, Percent Pore Volume	Oil Content After Pressure Reduction, Percent Pore Volume	Oil Recovered by Pressure Reduction, Percent Pore Volume
A	Loudon Crude	Methane	1,100	12	24.3	24.2	0.1	14.7	9.5
B	do	Nitrogen	1,630	12	22.2	22.0	0.2	13.1	8.9
C	do	Air	1,000	11.5	28.0	27.8	0.2	19.1	8.7
D	do	Flue Gas	825	15	34.1	33.9	0.2	24.5	9.4
E	do	Methane	930	16	32.4	32.3	0.1	23.1	9.2
F	Soltrol	do	470	12	35.3	35.1	0.2	22.3	12.8
G	do	Air	500	11	33.4	33.2	0.2	21.9	11.3
H	do	Methane	940	10	33.7	33.6	0.1	19.6	14.0
I	do	Air	1,000	11	33.9	33.7	0.2	21.0	12.7
J	do	Methane	1,100	9	33.2	32.7	0.5	18.9	13.8
K	do	Air	1,170	10	33.0	32.9	0.1	18.1	15.0
L	do	Methane	210	10	33.9	33.6	0.3	24.0	9.6
M	do	Air	200	10	33.9	33.7	0.2	26.7	7.1

From the above table it can be seen that driving gas through the watered-out cores did not permit the recovery of significant quantities of oil. This confirms earlier experience and is not unexpected, since it is known that waterflooding in general is considerably more effective than gas drive as a method for displacing oil from subsurface reservoirs. The data show, however, that the formation of a free-gas phase followed by a pressure reduction step resulted in the recovery of from about 20 percent to about 45 percent of the oil present in the cores following waterflooding. The process of the invention thus permits the recovery of significant quantities of oil which cannot be recovered by ordinary waterflooding and gas driving techniques.

The data set forth above also demonstrate that the process of the invention may be carried out with a variety of gases. Air, nitrogen, methane and flue gas all permitted the recovery of substantial quantities of oil. In most cases the results obtained with methane and flue gas were only slightly better than those obtained with air and nitrogen, indicating that gas solubility in the oil may be of some significance but that the effect due to solubility is small. The fact that substantial recoveries were obtained with both the Loudon crude oil and the refined white oil indicates that the process is not greatly dependent upon the properties of the oil in the reservoir and may be applied to reservoirs containing oils which vary considerably with respect to their composition, viscosity, gravity and other characteristics.

EXAMPLE II

A second series of experiments were carried out to determine the effect of pressure upon the process of the invention. The Weiler sandstone cores employed in the previous tests were cleaned, dried and resaturated with connate water and the refined white oil referred to earlier and then waterflooded until no more oil could be displaced. The oil content of the watered-out core was

determined for each run and was found to be about 33 to 34 percent in terms of core pore volume. From 9 to 12 percent methane or air, measured at the pressure selected and based upon core pore volume, was then injected into the core during each run. The pressures utilized ranged from 190 pounds per square inch to 1700 pounds per square inch. The fluids displaced from the cores were collected and analyzed. The oil recovered as a result of the gas drive ranged from 0.1 to 0.5 percent, based upon core pore volume. The cores were then depressurized and the fluids produced with the gas were collected and measured. The oil recovery during the pressure reduction stage of the process ranged from 8.3 percent of the pore volume at an initial pressure of 190 pounds per square inch to 16.4 percent of the pore volume at an initial pressure of 1700 pounds per square inch. The results of this second series of tests are set forth in greater detail in Table II below.

Table II

EFFECT OF GAS PRESSURE ON OIL RECOVERY FROM WATERED-OUT CORES

Run	Oil	Gas	Gas Pressure, p.s.i.	Gas Injected, Percent Pore Volume	Oil Content After Waterflood, Percent Pore Volume	Oil Content After Gas Drive, Percent Pore Volume	Oil Recovered by Gas Drive, Percent Pore Volume	Oil Content After Pressure Reduction, Percent Pore Volume	Oil Recovered by Pressure Reduction, Percent Pore Volume
A	Soltrol	Methane	190	9	33.5	33.3	0.2	25.0	8.3
B	do	do	210	10	33.9	33.6	0.3	24.0	9.6
C	do	do	450	9	33.8	33.7	0.1	21.2	12.5
D	do	do	470	12	35.3	35.1	0.2	22.3	12.8
E	do	do	900	9	33.7	33.5	0.2	20.2	13.3
F	do	do	900	9	33.3	33.2	0.1	19.2	14.0
G	do	do	940	9	34.3	34.1	0.2	20.9	13.2
H	do	do	940	10	33.7	33.6	0.1	19.6	14.0
I	do	do	1,100	9	33.2	32.7	0.5	18.9	13.8
J	do	do	1,700	9	33.5	33.3	0.2	16.9	16.4
K	do	Air	200	10	33.9	33.7	0.2	26.6	7.1
L	do	do	500	11	33.4	33.2	0.2	21.9	11.3
M	do	do	1,000	11	33.9	33.7	0.2	21.0	12.7
N	do	do	1,500	10	33.3	33.2	0.1	18.2	15.0
O	do	do	1,500	12	34.2	33.9	0.3	18.2	15.7
P	do	do	1,500	10	34.0	33.9	0.1	17.7	16.2
Q	do	do	1,500	10	34.0	33.9	0.1	21.2	12.7

The data in Table II show that the oil recovery from a watered-out core increases with increases in the initial pressure of the free-gas stage established in the core prior to the pressure reduction step. These data are presented graphically in the drawing, from which it can be seen that the recovery increases with pressure rapidly up to about 400 pounds per square inch and that the rate of increase is slower thereafter. Because the cost of compressing gas becomes prohibitively high at extremely high pressures, it is generally preferred to carry out the process of the invention at pressures between about 400 pounds per square inch and about 1500 pounds per square inch.

EXAMPLE III

Further tests were carried out to determine the effect of the volume of gas injected upon oil recovery. The procedure employed was essentially the same as in the earlier tests except that the injected gas volumes ranged from about 4.6 percent up to about 722 percent, based upon core pore volume. All the tests were carried out at a pressure of 1150 pounds per square inch. Air was employed as the injection gas and "Soltrol," a refined white oil, was used as the oil. Recovery during the pressure reduction step of the process ranged from 10.8 percent to 15.0 percent, based upon pore volume. The data obtained are shown in Table III.

Table III

EFFECT OF GAS VOLUME ON OIL RECOVERY

Run	Oil	Gas	Gas Pressure, p.s.i.	Gas Injected, Percent Pore Volume	Oil Content After Waterflood, Percent Pore Volume	Oil Content After Gas Drive, Percent Pore Volume	Oil Recovered by Gas Drive, Percent Pore Volume	Oil Content After Pressure Reduction, Percent Pore Volume	Oil Recovered by Pressure Reduction, Percent Pore Volume
A	Soltrol	Air	1,150	4.6	33.9	33.9	0	19.6	14.3
B	do	do	1,150	10	33.3	33.2	0.1	18.2	15.0
C	do	do	1,150	12	33.4	33.0	0.4	19.9	13.1
D	do	do	1,150	688	33.4	32.6	0.8	17.7	14.9
E	do	do	1,150	711	33.5	31.4	2.1	20.6	10.8

Inspection of the data set forth in Table III shows that increasing the volume of gas injected above 4.6 percent of the pore volume had little effect upon the oil recovery obtained. Substantially the same recovery was obtained by pressure reduction after 4.6 percent gas, based upon pore volume, had been injected as was obtained following the injection of much larger quantities of gas. In an actual reservoir, substantially less than 4.6 percent gas will normally be effective. The injected gas does not sweep the entire reservoir and hence the effective gas concentration in the swept area is higher than the volume of injected gas would indicate. For this reason, it is preferred to carry out the process of the invention by injecting only from about one percent to about twenty-five percent gas, based upon pore volume, into the reservoir. The fact that the injection of 722 percent gas resulted in the recovery of only 2.1 percent oil by gas drive in the above experiments clearly demonstraes that conventional gas drive processes applied to non-watered-out reservoirs are not effective after a waterflooding process has been carried out.

EXAMPLE IV

Still another series of tests was carried out to demonstrate single well application of the process of the invention. In these tests, cores of Weiler sandstone saturated with Soltrol and connate water were waterflooded in the manner previously described. During each run air was then injected into one end of the core under a pressure of 1150 pounds per square inch and displaced water was recovered from the other. After a measured volume of air had been injected in this manner, injection was halted and fluids were permitted to flow out the injection

inlet. It was found that substantial quantities of oil were produced from the cores in this manner. The results of these tests are set forth in Table IV.

Table IV

EFFECT OF PRESSURE REDUCTION ON RECOVERY FROM SINGLE WELL

Run	Oil	Gas	Gas Pressure, p.s.i.	Gas Injected, Percent Pore Volume	Oil Content After Waterflood, Percent Pore Volume	Oil Content After Gas Drive, Percent Pore Volume	Oil Recovered by Gas Drive, Percent Pore Volume	Oil Content After Pressure Reduction, Percent Pore Volume	Oil Recovered by Pressure Reduction, Percent Pore Volume
A	Soltrol	Air	1,150	4.3	34.1	34.1	0	27.2	6.9
B	do	do	1,150	4.5	33.8	33.7	0.1	27.6	6.1
C	do	do	1,150	12	33.9	33.7	0.2	21.9	11.8

As can be seen from the results shown in Table IV, the process of the invention can be applied to obtain additional recovery from a single well in a watered-out reservoir. The data show that the amount of oil recovered in this manner is slightly less than in the case where separate injection wells are used. Since the reservoir volume exposed to the effects of the injected gas is less where a single well is employed, the lower recovery is not unexpected. Recovery by means of a single well provides an attractive method for securing additional oil from many small watered-out fields.

EXAMPLE V

Tests similar to those described earlier were carried out to determine the effect of repeated repressuring and pressure reduction cycles in the process of the invention. The first of these utilized methane and "Wyrol," a heavy, refined white oil having a viscosity of about 45 centipoises. The core employed was first saturated with the Wyrol and connate water. After waterflooding until no more oil could be displaced, a free gas phase was established in the core by injecting methane at 1050 pounds per square inch. Twelve percent methane, based upon core volume and measured at ambient temperature and the injection pressure, was used. Reduction of the pressure resulted in the production of 6.4 percent oil, based on core volume.

The core was repressured to 1050 pounds per square inch and again the pressure was reduced. In this second cycle, 4.5% oil was recovered. A third cycle carried out in the same manner yielded 3.5% oil. In a fourth cycle, no additional recovery was obtained.

A second set of tests using methane and Wyrol confirmed the results obtained with the heavy oil. When repeated cycles were used with a methane-Soltrol system, however, no additional recovery resulted following the initial pressure reduction step. The results obtained in the two sets of tests using Wyrol appear in Table V.

Table V

EFFECT OF REPEATED CYCLES ON RECOVERY FROM WATERED-OUT CORES

Run	Oil	Gas	Gas Pressure, p.s.i.	Gas Injected, Percent Pore Volume	Oil Content After Waterflood, Percent Pore Volume	Oil Content After Gas Drive, Percent Pore Volume	Oil Recovered by Gas Drive, Percent Pore Volume	Oil Content After Pressure Reduction, Percent Pore Volume	Oil Recovered by Pressure Reduction, Percent Pore Volume
A	Wyrol	Methane	1,050	12	37.4	36.9	0.5	30.5	6.4
			Second Cycle						
	Do	do	1,050	12				26.0	4.5
			Third Cycle						
	Do	do	1,050	12				22.5	3.5
			Fourth Cycle						
	Do	do	1,050	12				22.5	0
B	Wyrol	Methane	1,050	12	36.2	36.1	0.1	28.2	7.9
			Second Cycle						
	Do	do	1,050	12				25.2	3.0
			Third Cycle						
	Do	do	1,050	12				25.2	0

It will be noted that repeated gas injection and pressure reduction steps permitted the recovery of substantially more of the heavy viscous oil than could be recovered in a single cycle. There are many watered-out reservoirs which contain such heavy oils and hence repeated cycles can often be employed to advantage. In reservoirs containing less viscous oils similar to Soltrol, repeated cycles have little effect.

It will be recognized that several modifications may be made in the process described above without departing from the scope of the invention. In many cases, for example, it may be desirable to inject gas into a watered-out reservoir through one well and to thereafter reduce the reservoir pressure and produce reservoir fluids through both that well and adjacent wells. This and other similar modifications will be readily apparent to those skilled in the art.

What is claimed is:

1. An improved process for recovering oil from a watered-out oil bearing reservoir underlying the earth's surface which comprises injecting a noncondensing gas into said reservoir through at least one well penetrating said reservoir, said gas being injected at a pressure within the range between about 100 and about 3,000 lbs. per square inch and in a quantity sufficient to establish a free-gas phase therein; discontinuing the injection of said gas; reducing the pressure on said reservoir; and producing reservoir fluids through at least one well penetrating said reservoir.

2. A process as defined by claim 1 wherein said gas is injected at a pressure of from about 400 to about 1,500 pounds per square inch.

3. A process as defined by claim 1 wherein said noncondensing gas injected into said reservoir is air.

4. A process is defined by claim 1 wherein said noncondensing gas injected into said reservoir is natural gas.

5. A process as defined by claim 1 wherein a noncondensing gas is reinjected into said reservoir and the pressure thereon is again reduced after the rate at which fluids are produced from the reservoir declines to an undesirably low level.

6. An improved process for augmenting production from a well penetrating a watered-out oil-bearing reservoir which comprises injecting from about 1 to about 25 percent, based upon reservoir pore volume and measured at the injection temperature and pressure, of a noncondensing gas through said well into said reservoir at a pressure of from about 100 to about 3000 pounds per square inch to establish a free-gas phase therein, discontinuing the injection of said gas, reducing the pressure on said well, and recovering oil, gas and water flowing into said well from said reservoir.

7. A process as defined by claim 6 wherein an exhaust gas from an internal combustion engine is injected into said reservoir as said noncondensing gas.

8. An improved process for recovering oil from a watered-out subsurface oil-bearing reservoir following a waterflooding operation which comprises injecting from about 1 percent to about 25 percent, based upon reservoir pore volume and measured at the injection temperature and pressure, of a noncondensing gas into said reservoir through at least one injection well at an injection pressure of from about 100 to about 3000 pounds per square inch whereby a free-gas phase is established in said reservoir; discontinuing the injection of said gas; reducing pressure on said reservoir at at least one production well spaced from said injection well; and withdrawing oil, water and gas flowing into said production well from said reservoir.

9. A process as defined by claim 8 wherein from about 1 percent to about 15 percent air, based upon reservoir pore volume and measured at the injection pressure, is injected into said reservoir as said noncondensing gas.

10. A process as defined by claim 8 wherein from about 1 percent to about 15 percent natural gas, based upon reservoir pore volume and measured at the injection pressure, is injected into said reservoir as said noncondensing gas.

11. A process as defined by claim 8 including the additional steps of discontinuing the withdrawal of fluids from said reservoir after substantially no more oil can be recovered, injecting a noncondensing gas into said reservoir through said injection well at a pressure of from about 100 to about 3000 pounds per square inch, reducing the pressure on said reservoir at said production well, and recovering additional oil from said production well.

12. A process as defined by claim 8 wherein, following injection of said gas at said injection well, the pressure on said reservoir is reduced at both said injection well and said production well and fluids are withdrawn from said reservoir through both said injection well and said production well.

13. A process is defined by claim 8 wherein said gas injected is a flue gas.

14. An improved process for recovering oil from a subterranean oil-bearing reservoir which comprises injecting water into said reservoir through at least one injection well, recovering fluids from said reservoir through at least one production well spaced from said injection well, continuing said injection of water and recovery of fluids until said reservoir is watered-out, thereafter injecting from about 1 to about 25 percent, based upon reservoir pore volume and measured at the injection temperature and pressure, of air into said reservoir through said injection well at a pressure of from about 400 to about 1500 pounds per square inch to establish a free-gas phase while maintaining a back pressure at said production well, discontinuing the injection of gas at said injection well, reducing the pressure on said reservoir at said production well, and recovering oil from said reservoir through said production well.

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