

Jan. 22, 1963

B. HABERMANN
METHOD FOR THE IMPROVEMENT OF AREAL SWEEP
DURING SECONDARY RECOVERY

3,074,481

Filed Sept. 25, 1959

3 Sheets-Sheet 1

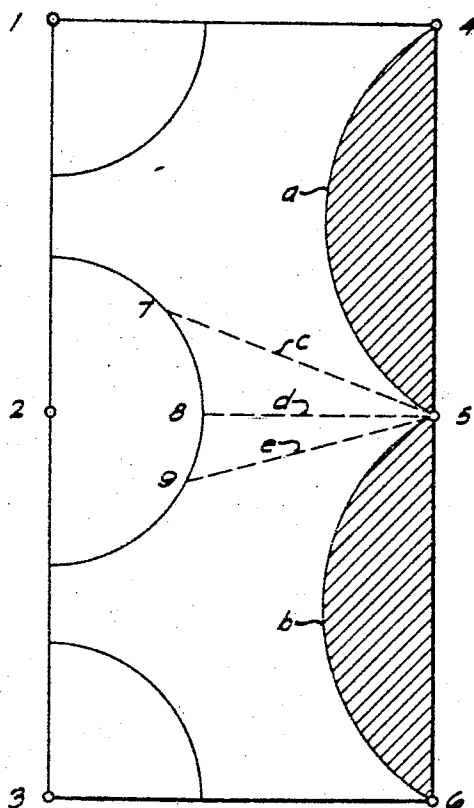


FIG. 1

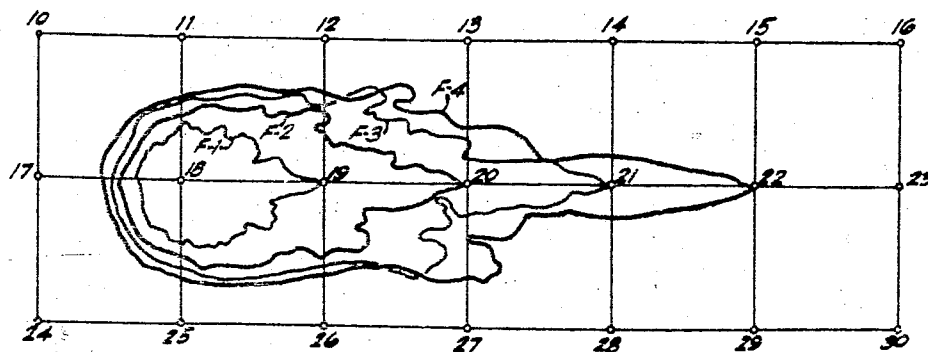


FIG. 2

INVENTOR.
BENZION HABERMANN
BY

Robert E. Evans
ATTORNEY

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3 Sheets-Sheet 2

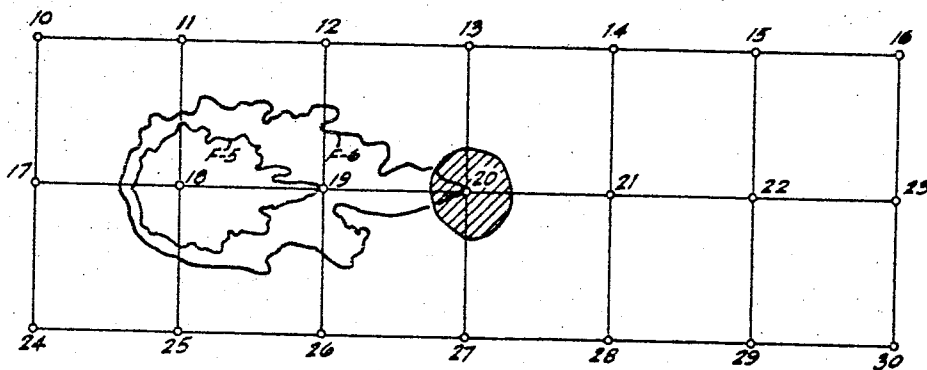


FIG. 3

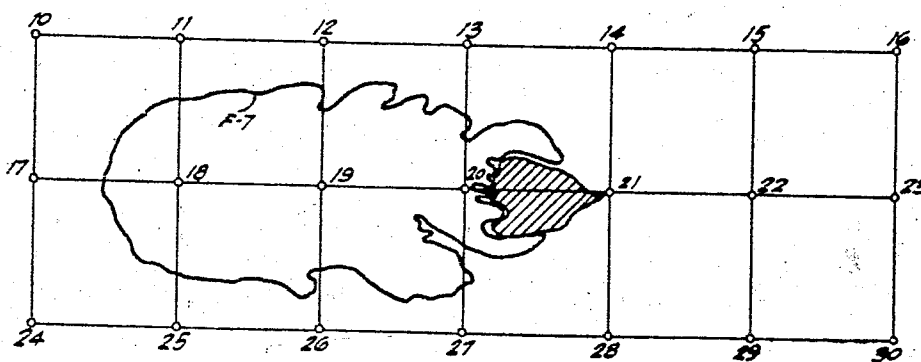


FIG. 4

INVENTOR.
BENZION HABERMANN

BY

Robert E. Haines
ATTORNEY

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3 Sheets-Sheet 3

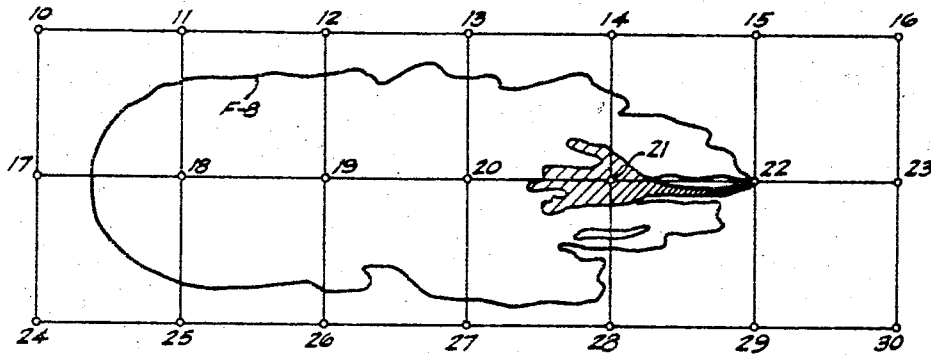


FIG. 5

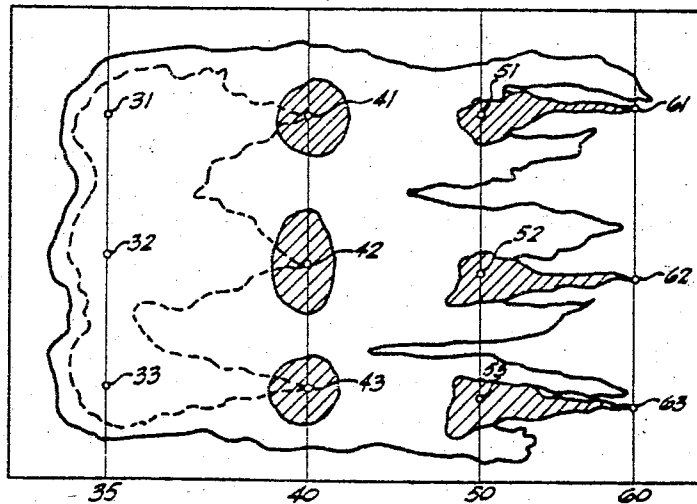


FIG. 6

INVENTOR
BENZION HABERMANN
BY

Robert J. Hume
ATTORNEY

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3,074,481

METHOD FOR THE IMPROVEMENT OF AREAL SWEEP DURING SECONDARY RECOVERY
Benzion Habermann, Montebello, Calif., assignor to
Union Oil Company of California, Los Angeles, Calif.,
a corporation of California

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14 Claims. (Cl. 166-2)

This invention relates to secondary recovery of petroleum from subterranean reservoirs. Specifically, this invention relates to a method for obtaining a high sweep efficiency of a displacing fluid through the reservoir.

In secondary recovery of petroleum from a reservoir, a widely accepted practice has been the injection of a fluid into the reservoir under sufficient pressure to force it through the reservoir to a producing well, thereby sweeping oil from the reservoir. The choice of injection and withdrawal wells is widely varied and depends on the type of secondary recovery process as well as the geometry of the reservoir. Among the techniques which have been employed are pattern drives, e.g., 5 spot, 7 spot, etc., which are commonly used with a liquid drive fluid such as water, and line or staggered line drives which are commonly employed with a gaseous drive fluid. Other techniques, such as edge and crestal injection are used when needed to suit the reservoir geometry.

A wide variety of fluids has been used or proposed for use as the displacing fluid, and these fluids may be conveniently grouped into a gas, liquid, or combined gas-liquid classification; the term "gas" as used herein being generic to those materials which normally exist in the gas phase under atmospheric conditions as well as those fluids which exist in the vapor state at the reservoir conditions. Examples of gas drive fluids are air, nitrogen, carbon dioxide, and various hydrocarbon gases, such as methane, ethane, and natural gas. Liquid displacement fluids, i.e., materials which are liquid or are in a critical phase above both their critical temperature and pressure at reservoir conditions, can be grouped into aqueous and non-aqueous liquids, examples of the latter including hydrocarbons such as liquefied petroleum gas (LPG), propane, butane, isobutane, pentane, isopentane, hexane, isohexane, crude oil, kerosene, gasoline, petroleum ether, xylene, toluene, benzene, coal tar oils, etc.; oxygenated compounds such as glycerol, phenol, methyl, ethyl, propyl, and isopropyl alcohols, acetone, acetaldehyde, propanol, etc. Examples of suitable aqueous drive fluids are water, brine, and aqueous solutions of various wetting or surface active agents and/or thickening agents, e.g., fatty acid soaps, alkyl pyridinium compounds, metal alginates, sodium lauryl sulfate, etc., as well as water soluble polymers such as polyvinyl or polyallyl alcohols, carboxymethyl cellulose, and partially hydrolyzed polyacrylamide. Because of their miscibility with crude oil, hydrocarbon drive fluids provide a more complete displacement of the reservoir oil than is obtainable with aqueous solutions; however, their relatively high cost offsets their efficient displacement, and water, with or without wetting, surface active, or thickening agents, is predominantly employed as a liquid drive fluid.

Combined gas-liquid and miscible liquid systems have also been used or suggested for use. Among such systems is the mixed gas and water phase drive which is achieved by the simultaneous injection of water and natural gas into a reservoir, and the various gas-hydrocarbon liquid drives which have recently received much attention. The latter displacement, frequently referred to as miscible phase or miscible slug displacement, involves first injecting into the reservoir a hydrocarbon which is either a liquid or in a critical phase above its critical temperature and pressure at the reservoir condi-

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tions and which is miscible with the reservoir oil, and then driving the injected hydrocarbon slug through the reservoir with a gas or a combined gas-water mixture which is also miscible with the liquid slug. A modification of this process employs a slug with a graduated concentration of hydrocarbon liquid and drive gas to avoid a sharp interface between the drive gas phase and the slug phase. Hydrocarbon liquids employed in these processes have been LPG, butane, crude oil, and petroleum distillates.

A third type of miscible fluid displacement process herein considered as a liquid drive system is the high pressure condensing gas method wherein a gas, such as natural gas, is injected at pressures in excess of about 3,000 p.s.i., into the reservoir. The advancing front of gas acts as a solvent to dissolve light fractions of the reservoir oil and thereby form, in situ, a liquid slug phase which is between the remaining gas drive and the reservoir oil and is miscible with each.

Another type of miscible fluid displacement involves the injection of a liquid which is miscible with the reservoir oil and with water which is employed as the drive fluid. Various alcohols, such as methyl, ethyl, propyl, isopropyl, and butyl alcohol, phenol, glycerol, etc.; ketones, such as acetone, butanone, etc.; aldehydes, such as acetaldehyde, propionaldehyde, etc.; and various other solvents such as carbon tetrachloride, methyl chloride, dimethylether, sulfur dioxide, and dichloro-difluoromethane can suitably be used. Because many of these solvents frequently have a viscosity which is less than that of the reservoir oil and/or water drive, viscosity additives such as gums, resins, and crude sugars can be added to increase their viscosity.

The invention is described below with reference to the figures of which:

FIGURE 1 illustrates a conventional line drive fluid displacement process under ideal conditions,

FIGURE 2 is a map of actual flow conditions of a fluid displacement process in a laboratory model as described in Example I,

FIGURES 3, 4 and 5 are maps of actual flow conditions of the fluid displacement process with application of the invention as described in Example II, and

FIGURE 6 illustrates a flow pattern typical of the invention as applied to a line drive fluid displacement process.

Common to all these types of secondary recovery is the problem of obtaining satisfactory distribution of the injected fluid throughout the reservoir, since the latter is not a homogenous mass having the same structure throughout, but, rather, contains zones having different permeabilities and fissures, cracks, or channels having relatively high permeability to the injected fluid. These irregularities tend to direct the flow of the injected fluid into narrow fingers or channels through the reservoir rather than as a smoothly advancing front, by-passing much of the reservoir oil which is never recovered. This fingering tendency of the injected fluid is also caused by the indiscriminate choice of fluids having very low viscosities relative to the reservoir oil since it is related to the mobility ratio between the reservoir oil and the injected fluid. The mobility of a fluid within a reservoir is defined as the ratio of the reservoir's permeability to the fluid in darcy units divided by the viscosity of the fluid in centipoises. Therefore, the mobility ratio, M , is defined as follows:

$$M = \frac{\frac{K_2}{\mu_2}}{\frac{K_1}{\mu_1}} = \frac{\mu_1}{\mu_2} \times \frac{K_2}{K_1}$$

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where

μ_2, μ_1 = viscosity of displacing fluid and displaced fluid, respectively; and

K_2, K_1 = permeability of the reservoir with respect to the displacing fluid and displaced fluid, respectively.

Even for a mobility ratio of one or less, it has been observed that only about 70 percent of the reservoir area will be covered by the displacing fluid. This is entirely due to the geometry of the system as shown diagrammatically in FIGURE 1 which represents a typical line drive during and immediately after a displacement process. As illustrated, a displacing fluid is injected into the left row of wells 1, 2 and 3, and oil is withdrawn from the right row of wells 4, 5 and 6. The advancing fluid front is shown in intermediate positions by the circular arcs around injection wells 1, 2 and 3 and in its final position by arcs *a* and *b* between wells 4 and 5 and 5 and 6, while the shaded area represents that portion of the reservoir not swept by the injected fluid. The reason for this anomalous flow distribution is apparent from a study of the geometry of the system shown by points 7, 8 and 9 on the central circular arc. Point 8, on the advancing front lies directly between injection well 2 and production well 5 and is closer to well 5 than any other point on the fluid front, such as 7 and 9. The resistance to fluid flow from point 8 to well 5 is proportional to distance *d* which can be seen to be less than distances *c* or *e* for points 7 and 9, respectively. Accordingly, point 8 advances more rapidly to well 5 than do points 7 or 9, resulting in the final front assuming the shape shown by lines *a* and *b*.

From the foregoing, it is apparent that satisfactory flow distribution of a displacement fluid through a reservoir is difficult to achieve and that, even with addition of viscous additives to the displacing fluid to achieve favorable mobility ratios, a complete areal sweep of the fluid is not possible with customary secondary recovery techniques.

It is a purpose of this invention to improve the sweep efficiency in secondary recovery by the fluid displacement method.

This purpose is achieved by the novel injection and displacement method of this invention which, in its simplest form, comprises: first, injecting a displacement fluid into the reservoir through a first well communicating with the reservoir. The displacement fluid can be any of the numerous aforementioned fluids or combinations thereof which have been used or suggested for use in secondary recovery. Concurrently with this injection, or if desired at a later time after the reservoir has been pressurized, withdrawal of oil is initiated from a second well spaced apart from said first well. These wells will usually, but not necessarily, be wells which were drilled during the previous primary production from the reservoir. For the ideal case, with a mobility ratio of the displacing fluid to the oil phase of one or less and with a reservoir free from zones having different permeabilities and extensive fractures or fissures, the displacing fluid will advance uniformly as a smooth front until it nears the withdrawal well where the localized withdrawal of the oil at the well will elongate that portion of the front lying directly between the withdrawal and injection well. At this point in the operation, production from the second well is stopped, and a viscous fluid is injected into the reservoir through the second well and, withdrawal of the oil from the reservoir is initiated at a third well spaced apart from said second well and so located that the displacing fluid will continue to move in the same general direction. The viscous liquid is thus injected into the reservoir at the most extended or elongated portion of the advancing fluid front. Because of its high viscosity, this liquid effectively slows or retards the advance of the leading or elongated region of the front, but since the viscous liquid is not in the flow path of the trailing portion of the

fluid front it does not slow down this portion. The effect of this injection, therefore, is to even the front by increasing the rate of advance of the trailing portions relative to the elongated portions. The viscosity and quantity of the viscous fluid which is injected into the second well can be readily controlled to produce a zone of any volume and viscosity, for instance, a relatively expanded zone of moderate viscosity, or a concentrated zone with a high viscosity depending on the size and degree of elongation of the leading portions of the front. As the front advances, the injected viscous liquid tends to distribute itself across the front with the greatest concentration at the most forward point of the front as it is slowly forced towards the producing well. After sufficient viscous liquid has been added to retard fingering of the displacing fluid, the second well can be closed off or alternatively switched to injection of the displacing fluid in combination with, or in substitution for, the injection of the displacing fluid through the first well. After the fluid front has reached the third well and again becomes deformed with elongated portions at each well site, the procedure is repeated and a fourth row of wells is put on production to withdraw the displaced oil. This procedure is repeated as many times as may be desired or as may be necessary to sweep the entire reservoir.

The viscous liquid which is injected into the reservoir can suitably comprise any of a number of viscous liquids which do not plug or seal off the formation and which are more viscous than either the reservoir oil or the displacement fluid. Generally, a liquid is employed which has a viscosity $1\frac{1}{2}$ to 20 times greater than either the reservoir oil or displacement fluid viscosity, whichever is greater, and preferably a liquid which has a viscosity 2 to 10 times greater.

Liquids suitable for use as the viscous liquid of the invention can be for instance; water; brine; hydrocarbons, such as aromatics, e.g., benzene, toluene, xylene, etc., crude oil and fractions thereof, e.g., distillates, reduced crude, tar, pitches, and waxes (the latter substances are to be used with caution to avoid plugging the formation); oxygenated compounds, such as alcohols, e.g., methyl, ethyl, normal and iso propyl, butyl, amyl alcohol, phenol, glycol, glycerol, etc., ethers, e.g., methy ethyl ether, dimethyl diethyl ether, etc., ketones, e.g., acetone, butanone, etc., and aldehydes, e.g., acetaldehyde, propionaldehyde; and various other solvents such as acetonitrile, acrylonitrile, carbon tetrachloride, methyl chloride, sulfur dioxide, and dichloro-difluoromethane. The purpose of the invention can be achieved whether or not the viscous liquid is miscible with the reservoir oil; however, it is preferred to employ a liquid which is miscible with both the reservoir oil and the displacement fluid to obtain a more complete recovery of oil. When water or a hydrocarbon gas is employed as the displacement fluid, such miscibility can be achieved by use of solvents miscible with water or the hydrocarbon gas and reservoir oil, e.g., any of the aforementioned oxygenated compounds, and other solvents as acetonitrile, acrylonitrile, carbon tetrachloride, methylchloride, sulfur dioxide, and dichloro-difluoromethane. Because these liquids have relatively low viscosity, various viscosity additives must be employed in admixture with them, e.g., sugars, gums, resins, and glucosides, can be added to increase the solvent viscosity. Examples of gum and resin solutions are: gum benzoin, rosin, ester gum, or sandarak in acetone, gum benzoin, elemi, ester gum, gum mastic, kauri, rosin or sandarak in phenol, normal and isobutyl alcohol, n-butyl glycol, cyclohexanone, ethyl ether, ethyl glycol, methyl alcohol, methyl glycol, methylene chloride, and normal and isopropyl alcohol. An example of a crude sugar in a solvent is fructose in alcohol or acetone, while various glucosides, such as absinthin, aesculin, antiarin, cerberin, convallamarin, coriamyrtin, curangin, digitalin, digitonin, digitoxin, glucogallin, glycovanillin, glycyphyl-

lin, gratolin, indican, piclin, picrocrocin, tannic acid, and thevetin can be used in an alcohol or ether solution, such as methyl, ethyl, normal and isopropyl alcohol, or dimethyl ether, diethyl ether, etc.

The invention can also be practiced by use of water as the viscous liquid when the reservoir oil and the displacement fluid have a viscosity less than the injected water. Frequently, however, the reservoir oil has a viscosity greater than water and in these cases as well as those cases in which water is used as the displacement fluid, it is within the scope of this invention to add various thickening agents to form a viscous aqueous solution for use as the viscous liquid. Suitable agents are crude sugars, sucrose, fructose, galactose, etc.; the aforementioned glucosides; fatty acid soaps and metal alginates; as well as various water-soluble polymers such as carboxymethyl cellulose, polyvinyl and polyallyl alcohols, and partially hydrolyzed polyacrylamides.

Suitable partially hydrolyzed acrylamide polymers are water-soluble acrylamide polymers which have been hydrolyzed to such an extent that between about 0.8 and 10 percent of the amide groups have been converted to carboxyl groups. As herein employed, the term "acrylamide polymer" is inclusive of the homopolymers of acrylamide, i.e., polyacrylamide, and water-soluble copolymers of acrylamide with up to about 15 percent by weight of other polymerizable vinyl compounds, such as the alkyl esters of acrylic and methacrylic acids, methacrylamide, styrene, vinyl acetate, acrylonitrile, methacrylonitrile, vinyl alkyl ethers, vinyl chloride, vinylidene chloride, etc. In addition to the aforementioned limitation on the extent of hydrolysis, the suitable acrylamide polymers are of sufficiently high molecular weight that a 0.5 percent by weight aqueous solution thereof has a viscosity of at least 4 centipoises Ostwald at 21.5° C. A commercially available polymer meeting these requirements is marketed by The Dow Chemical Company under the name "Separan." The above-mentioned polymers are preferred for an aqueous viscous liquid, since they form stable solutions and do not easily precipitate when heated or when in the presence of mineral anions and cations; however, the use of any other water-soluble material which forms a stable viscous aqueous solution is also within the scope of the present invention. Rather than using a viscous hydrocarbon fraction, a viscous solution of a hydrocarbon and a high viscosity additive can be employed. A group of compounds which show great increases in solution viscosity for relatively low concentrations in hydrocarbon are the oil-soluble long chain polymers. The increase in viscosity effect noted with solutions of such polymers is related to the molecular weight and shape of the polymer chain. The relationship between viscosity and molecular weight is as follows:

$$[n] = KMa$$

where

K and a are constants for a given series of polymers; M equals the polymer molecular weight;

n is the intrinsic viscosity and is obtained by extrapolating to zero concentration a plot of:

$$\frac{1}{C} \left[\frac{n - n_0}{n_0} \right]$$

versus. concentration, where

C = concentration;

n = viscosity of solution;

n_0 = viscosity of solvent.

The values of K and a are reported in available literature on polymers, e.g., Synthetic Rubber, by G. S. Whitby, p. 331.

Any long chain oil-soluble polymer exhibiting a high solution viscosity is appropriate for use in accordance with the invention. Examples of suitable polymers are: polymers of butadiene, isobutylene, chloroprene, co-

polymers of butadiene and styrene, methyl methacrylate, or acrylonitrile, copolymers of isobutylene and isoprene, natural rubber, and polyvinyl chloride plasticized with tricresyl phosphate. The above formulas show that the

increase in viscosity of a polymer solution is a direct function of the polymer molecular weight. Expressed in another form, the formulas show that the greater the polymer molecular weight, the lower the concentration of the polymer needed to achieve any given solution viscosity. The maximum molecular weight of polymers useful in this invention is limited only by the solubility of the polymer in the miscible displacement fluid. Although the lower molecular weight polymers are more soluble, their use is disadvantageous since relatively large quantities of the polymer must be added to achieve a satisfactory viscosity increase. The preferred polymers are those which effect a substantial increase in the viscosity of the solution at concentration less than about 1 percent by weight, and which have molecular weights greater than about 10,000 and preferably between about 500,000 and 1,500,000. Sufficient polymer is added to the hydrocarbon liquid to cause more than a 10 percent increase in viscosity. The amount of polymer added varies for each polymer but is generally between 0.01 and 10 percent by weight, and preferably from 0.05 to 5 percent by weight. The hydrocarbon solvent can be any liquid in which the polymer can be dissolved and which preferably, but not necessarily, is miscible with the reservoir oil and the displacement fluid. Examples of solvents include petroleum distillates, crude oil, petroleum ether, paraffin hydrocarbons such as propane, butane, pentane, hexane, heptane, LPG, etc.; aromatics, such as xylene, toluene, benzene, coal tar oils, cyclohexane, or mixtures thereof. Preferred fluids are LPG, propane, butane, isobutane, pentane, isopentane, hexane, isohexane, gasoline and kerosene. The optimum combination of polymer and solvent will, of course, be dictated by reservoir characteristics, economic considerations and extent of elongation of the displacing fluid front.

The invention has particular advantage when applied to a miscible fluid displacement process employing a miscible slug comprising a hydrocarbon-polymer solution. In this process, a long chain oil-soluble polymer, for example, polyisobutylene, is dissolved in a low molecular weight hydrocarbon solvent such as pentane, and a sufficient amount of the solution is injected into the reservoir to insure separation between the reservoir oil and a subsequently injected gaseous drive fluid. Ordinarily, the use of low molecular weight hydrocarbons in this manner is somewhat unsatisfactory from the standpoint of cost, since the suitable hydrocarbons are either relatively expensive per se or must be used with a relatively expensive secondary solvent in order to dissolve an effective amount of the polymer.

The process of the present invention, however, permits the use of inexpensive lower members of the aliphatic hydrocarbon series, e.g., LPG, propane, or butane, as the miscible hydrocarbon liquid without the need of an expensive secondary solvent to dissolve the polymer. This is accomplished in accordance with the following procedure: A sufficient quantity of LPG is injected into the reservoir to insure separation of the reservoir oil and a subsequently injected gaseous drive fluid, e.g. methane. This requires from about 3 to 15 volume percent of the reservoir pore volume, and is dependent upon the mobility ratio between the LPG and reservoir oil, being about 3 percent for a mobility ratio of one or less and about 10 percent for a mobility ratio of about 50. The slug of LPG thus injected is followed by the injection of methane. As the miscible LPG slug is driven towards the producing well by the methane, the low viscosity LPG will finger through the reservoir to the producing well as previously explained. As the front advances, mixing between the miscible LPG and reservoir oil will occur, and when the slug fingers into the pro-

ducing well it will have been enriched with the reservoir oil. Although the LPG slug originally injected into the reservoir had very little solubility for a viscous long chain polymer, the slug as it reaches the producing well, enriched with oil, has a high solubility for such a polymer. A concentrated solution of polyisobutylene in a solvent such as pentane, benzene, or crude oil can, therefore, be injected into this well before it is closed and the polymer will dissolve in the slug to provide a very viscous region adjacent the finger. A third well is then opened to continue the advancement of the slug in the same general direction, and after the slug has completely swept past the closed second well, this well can be switched to injection of methane, and the first well can be closed. To insure that the polymer solution is injected from the second well directly into the finger, the third well can be opened to production and the second well temporarily closed prior to polymer injection so as to draw the finger beneath the second well. Thereafter, the second well is opened and the polymer solution injected directly into the finger. Because of the local high viscosity of the slug at its most advanced or fingered position, the fingering tendency is effectively corrected and the miscible fluid advances towards the third well more evenly. This same procedure can be followed along a continuous row of wells in a field, i.e., a first well or row of wells can be employed for injection, and a second, third, fourth, etc., row of wells are then employed in the following sequence of steps: (1) withdrawal; (2) polymer solution injection; (3) closed in; and (4) gas drive injection; until the miscible slug phase has swept through the entire reservoir.

The invention will be further described by the following examples which are for illustration only and are not to be considered as limiting the invention:

EXAMPLE I

A consolidated sandstone plate, with a porosity of about 30 percent, one-eighth inch thick, 21 inches wide and 7 inches long, was sealed between two plates of Lucite. Two rows of 7 holes each were drilled into one of the Lucite plates, equally spaced along the length of the plate adjacent each of the longer edges. A third row of similarly spaced holes was drilled along the mid-line of the plate to divide the plate into twelve squares, three and one-half by three and one-half inches. These squares are shown by the faint grid lines of FIGURES 2, 3, 4 and 5, which also show the numbering of the holes from left to right, from the upper row to the lower row. Tubing connections were inserted into the holes to permit passage of fluids through the sandstone model. The latter was then saturated with clear kerosene having a viscosity of 1.76 centipoises at room temperature (75° F.). The model was held in a horizontal plane above a light source to permit observance of the flow pattern during the run. A run typical of conventional practice was commenced by injecting a red displacing fluid, consisting principally of hexane and having a viscosity of 0.32 centipoises at room temperature, into well 18 while withdrawing clear kerosene from well 19. This injection was continued until a red displacing fluid finger broke through to well 19, whereupon wells 18 and 19 were closed and the flow pattern was traced onto a sheet of clear plastic placed over the model. This tracing is shown in FIGURE 2, as fluid front F-1. The run was continued by repeating the injection of the displacing fluid into well 18 (well 19 being closed) and withdrawing from well 20 until the displacing fluid broke through to well 20. The flow pattern was traced and is shown in FIGURE 2 by fluid front F-2. This procedure was repeated, employing wells 21 and 22 successively as withdrawal wells and continuing injection into well 18. The fluid fronts at breakthrough to wells 21 and 22 are shown by F-3 and F-4, respectively. During the run the displaced kerosene volume was meas-

ured and recorded at breakthrough into each well and these results appear in the following table:

Table 1

[Conventional displacement—volume kerosene displaced at breakthrough]	
Well:	Total, milliliters
19	2.6
20	7.6
21	13.2
22	18.0

EXAMPLE II

The sandstone model was flushed clean and again saturated with clear kerosene, and the procedure of Example I was repeated, again employing red hexane as a displacing fluid. Viscosities of the kerosene and hexane were the same as in Example I. The displacing fluid front at breakthrough to well 19 is shown as F-5 and at breakthrough to well 20 as F-6 in FIGURE 3. At this point the invention was applied by the injection of a mixture of oil and kerosene having a viscosity of 5 centipoises into well 20 with wells 13 and 27 open to withdraw the displaced kerosene. A blue dye was added to this viscous liquid to identify it during the test. The injected slug of viscous liquid after injection is shown by the shaded area surrounding well 20. During injection of this viscous slug, no noticeable shifting of fluid front, F-6, occurred. After two milliliters of the viscous fluid had been injected into well 20, wells 13, 20 and 27 were closed, well 18 was reopened to injection of the hexane displacing fluid, and well 21 was opened to withdrawal of kerosene. After breakthrough to well 21 of the viscous liquid slug, wells 18 and 21 were closed and the flow patterns were traced to obtain FIGURE 4 which shows the displacing fluid front as F-7 and the viscous liquid slug as the shaded area. Thereafter, injection into well 18 was repeated, with well 22 opened for withdrawal of kerosene. The displacing fluid and viscous liquid slug both fingered into well 22, at which point wells 18 and 22 were closed, and the flow pattern was traced to obtain FIGURE 5. The fluid front of the displacing fluid is shown as F-8 and the viscous liquid slug as the shaded area in FIGURE 5. The displacing fluid and viscous liquid mixed along their interface, this being indicated in FIGURE 5 by the less dense shading of the trailing portion of the viscous slug. As in Example I, the volume of displaced kerosene was measured and recorded at breakthrough to each well. This data appears in the following table:

Table 2

[Typical of the invention—volume kerosene displaced at breakthrough]	
Well:	Total, milliliters
19	2.4
20	7.7
21	*14.5
22	*23.2

* Does not include the two milliliters withdrawn from wells 13 and 27 during injection of the viscous liquid slug.

A visual comparison of FIGURES 2 and 5 shows that the total area swept by the displacing fluid and viscous slug in FIGURE 5 is much greater than obtained without use of viscous liquid injection as shown in FIGURE 2. In FIGURE 2 it can be seen that the fluid front rapidly narrowed into a finger extending past wells 20 and 21, to well 22. A comparison of the amount of kerosene displaced shows that even when disregarding the two milliliters displaced by injection of the viscous liquid slug, the total recovery of Example II is 28.9 percent greater than that of Example I. The actual recovery, including the two milliliters produced through wells 13 and 27, is 40 percent greater.

The invention has been illustrated in the foregoing

examples under ideal reservoir conditions, i.e., with a reservoir having a uniform permeability throughout, and with a fluid mobility ratio of displacing hexane to kerosene of 1.76/0.32, or 5.5, a value usually exceeded under actual reservoir conditions. The effect of these conditions has been to minimize fingering in the model so as to obtain flow patterns which may be readily evaluated. Under actual reservoir conditions, the displacing fluid fingering will be more pronounced and, therefore, the improvement of the sweep efficiency of the displacing fluid when the viscous liquid slug of the invention is employed will exceed that observed in the laboratory studies.

Although the invention has been described with regard to the horizontal sweep efficiency of the displacement, in actual use it can also be applied to obtain a satisfactory vertical sweep efficiency. In this use, the vertical location of the finger is located by any suitable method, such as by sealing off various heights of the producing borehole until the region producing the displacement fluid is located. This zone is then sealed off with packers and the viscous liquid slug is injected into this zone, thereby insuring that the greatest mass of viscous liquid will be concentrated at the exact spacial location of the finger.

The invention has been described by reference to a displacement process between a single injection well and successive withdrawal wells. This was to illustrate the invention in its simplest form; in field use, a plurality of wells can be employed for injection and/or withdrawal. A type flow pattern which can be expected when the invention is applied to one of the conventional drive techniques, i.e., a line drive, is shown in FIGURE 6.

FIGURE 6 illustrates a typical flow pattern in which a displacing fluid which has been injected into the reservoir through a first row of injection wells, 35, has the intermediate front shown by the dashed lines at breakthrough into a second parallel row of withdrawal wells, 49. When the fingering of the fluid is pronounced as shown by FIGURE 6, slugs of viscous liquid are injected into each producing well. During this injection of viscous slugs, the displaced reservoir oil is withdrawn from the next succeeding parallel row of wells, or from adjacent wells in the same row as the well used to inject the viscous slug. Alternatively, when it is desired to repressurize the reservoir, no withdrawal of reservoir oil is made. When the wells are closely spaced and the injected liquid is not extremely viscous, the shape of the injected viscous slug can readily be controlled by proper choice of withdrawal wells during injection. This is illustrated in FIGURE 6 by the various shaped areas surrounding wells 41, 42 and 43. The slug injected into well 41 illustrates a zone having a circular horizontal cross section, typical of injection into a reservoir when withdrawal is from a well or wells spaced a substantial distance from that employed to inject the viscous slug and/or when an extremely viscous liquid is injected into a reservoir, or when no withdrawal of reservoir oil is made. The elliptical shaped slug at well 42 represents injection of a relatively low viscosity liquid into the reservoir while the displaced reservoir oil is withdrawn from adjacent wells 41 and 43. This method is preferred since it distributes the greatest portion of the slug transverse to the direction of fingering. Well 43 is shown with a slug having a circular horizontal cross section obtained by viscous liquid injection without any withdrawal of reservoir oil. The amount of slug injected into each well is directly proportional to the extent of fingering occurring at each well site as determined, for instance, by the relative production from each well. It is, of course, apparent that in the extremely rare instance where no finger has formed adjacent a withdrawal well, no viscous slug need be injected.

After the viscous slugs have been injected into the wells of row 40, these wells are closed and reservoir oil

is withdrawn from the wells in row 50. After the displacing fluid or viscous liquid reaches the wells in this row, they are closed to production and reservoir oil is withdrawn from the next succeeding row 60, or if the extent of fingering is again pronounced, additional slugs of viscous liquid are injected through the wells in row 50. FIGURE 6 shows the fluid front as it reaches the withdrawal wells in row 60 and it can be seen that substantially all the area between rows 35, 40 and 50 has been swept by the fluid.

In another modification of the line drive method of the invention, not all the wells of a single row are employed for injection of the viscous slug. For instance, every second or third well in row 40 can be employed for slug injection, such as injection through wells 41 and 43. In the succeeding parallel row of wells 50, viscous slugs are injected through wells opposite those wells of the preceding row which were not employed for viscous slug injection, in this case, well 52. This modification can suitably be used when it is desired to elongate the slug in a direction at right angles to the fluid flow direction, since wells adjacent the well employed for slug injection are available for withdrawal of displaced oil.

From the foregoing illustrations, it is obvious that the number and location of injection and/or withdrawal wells can be varied so as to obtain substantially any desired flow pattern or sweep in a secondary recovery process.

Having clearly, completely and concisely described my invention, I therefore claim:

1. The method of recovering oil from a subterranean reservoir pierced by at least three wells consisting of an input well, a second well spaced a substantial distance therefrom and a third well located between said input and second wells which comprises: injecting a displacement fluid into said input well; withdrawing said oil from said reservoir through said third well until the presence of said displacement fluid is detected in the effluent from said third well; thereafter, ceasing said withdrawal of said oil from said third well and injecting a slug of viscous liquid into said reservoir through said third well, said viscous liquid having a viscosity at reservoir conditions greater than the viscosity of the most viscous of said first displacement fluid and said oil, the viscosity and amount of said viscous liquid being sufficient to substantially retard the advance of said displacement fluid in the vicinity of said third well bore; thereafter shutting in said third well and withdrawing said oil from said second well while continuing to inject said displacement fluid into said input well.

2. The method of claim 1 wherein said displacement fluid is an aqueous liquid.

3. The method of claim 2 wherein said viscous liquid is an aqueous solution of a water-soluble thickening agent selected from the group consisting of: crude sugars, glucosides, fatty acid soaps, alginates, and water-soluble polymers.

4. The method of claim 2 wherein said viscous liquid comprises a liquid which is miscible with said reservoir oil and with water and contains a thickening agent selected from the group consisting of crude sugars, gums, resins and glucosides.

5. The method of claim 2 as applied to a miscible displacement process wherein said displacement fluid comprises a slug of hydrocarbon which is liquid at reservoir conditions and which is first injected into said input well and a drive gas which is thereafter injected into said input well.

6. The method of claim 1 wherein said displacement fluid is a gas.

7. The method of claim 6 wherein said viscous liquid is an aqueous solution of a water-soluble thickening agent selected from the group consisting of: crude sugars, glucosides, fatty acid soaps, alginates, and water-soluble polymers.

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8. The method of claim 6 wherein said viscous liquid comprises a liquid which is miscible with said oil.

9. The method of claim 8 wherein said viscous liquid contains a thickening agent selected from the group consisting of long chain oil-soluble polymers, crude oil, crude oil distillates, and mixtures thereof.

10. The method of claim 9 as applied to a miscible displacement process wherein said displacement fluid comprises a slug of hydrocarbon which is liquid at reservoir conditions and which is first injected into said input well and drive gas which is thereafter injected into said input well.

11. The method of obtaining oil from a subterranean reservoir pierced by a plurality of wells substantially arranged to form at least first, second and third consecutive parallel rows of wells which comprises: injecting a displacement fluid into said reservoir through wells in said first row; withdrawing said oil from said reservoir through wells in said second row; ceasing said withdrawal at each of said wells in said second row when said displacement fluid is present in the effluent therefrom; injecting a viscous liquid into each of said wells of said second row from which withdrawal has ceased; said viscous liquid being more viscous than most viscous of said displacement fluid and said oil; the viscosity and amount of said viscous liquid being sufficient to substantially retard the advance of said displacement fluid in the vicinity of said third well bore; closing said wells in said second row, withdrawing oil from wells in said third row and continuing to inject said displacement fluid through said wells in said first row.

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12. The method of claim 11 wherein said viscous liquid is injected into said reservoir through alternate wells in said second row, while withdrawal of displaced fluids from said reservoir is conducted from the wells adjacent said alternate wells in said second row during the injection of said slug of viscous liquid.

13. The method of claim 11 wherein withdrawal of said oil through wells in said third row is initiated simultaneously with said injection of said slug of said viscous liquid into said reservoir through said wells in said second row.

14. The method of claim 11 wherein consecutive parallel rows of wells are successively employed in the sequence of: first, withdrawal of displaced oil; second, injection of viscous liquid; third, closed.

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