May 16, 1967 O. T. MOORE 3,319,713

METHOD OF DETERMINING THE OIL AVAILABILITY CONTOUR OF AN OIL FIELD

Filed Feb. 11, 1964 3 Sheets-Sheet 1

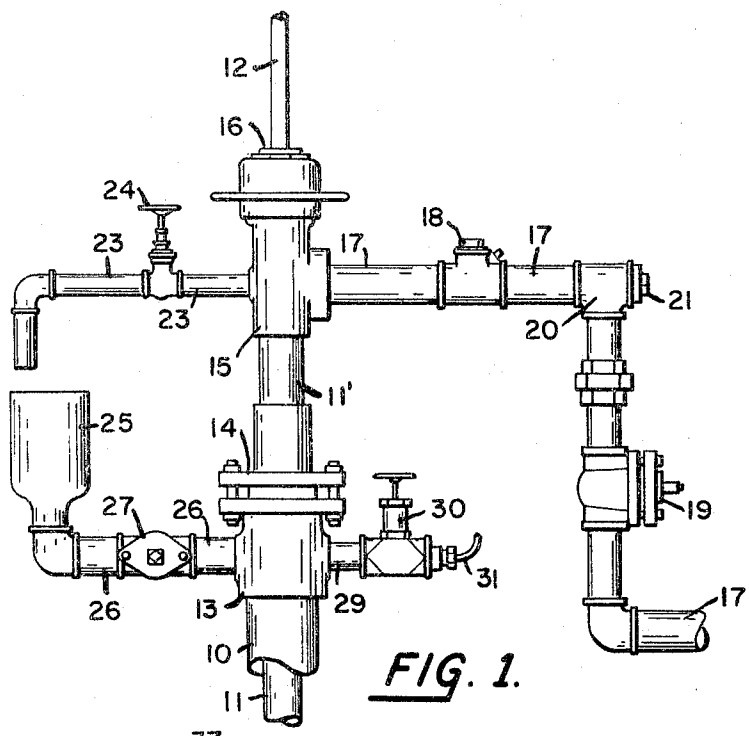


FIG. 1.

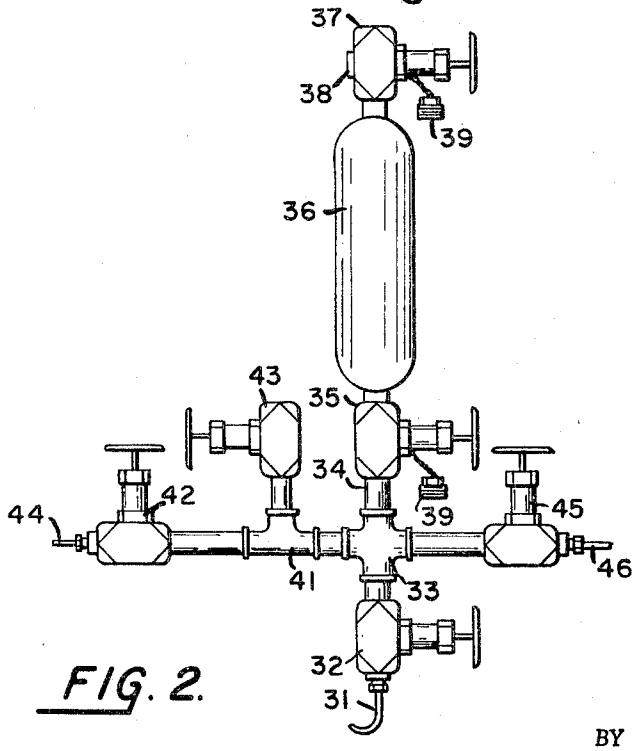


FIG. 2.

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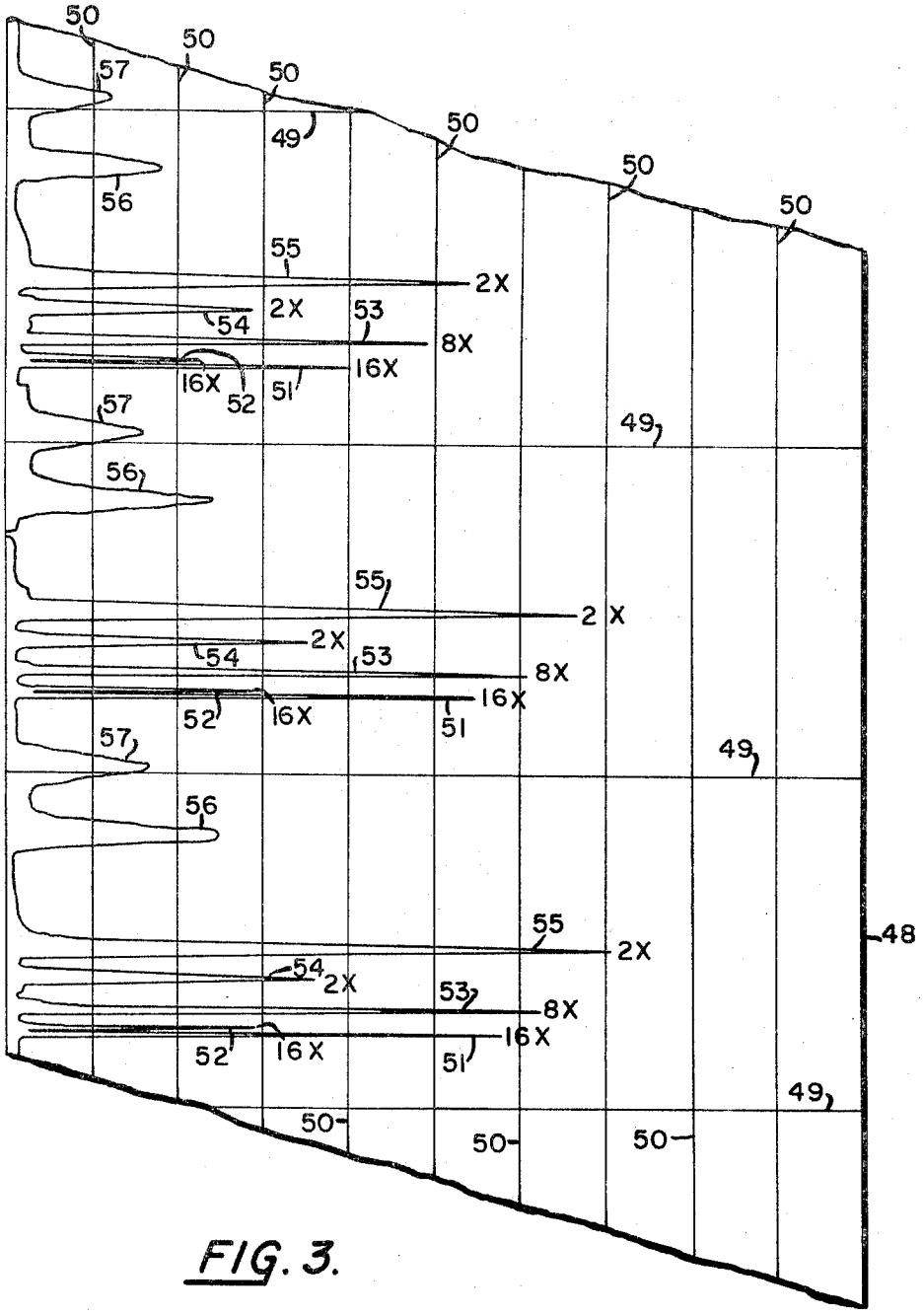


FIG. 3.

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METHOD OF DETERMINING THE OIL AVAILABILITY CONTOUR OF AN OIL FIELD

Filed Feb. 11, 1964 3 Sheets-Sheet 3

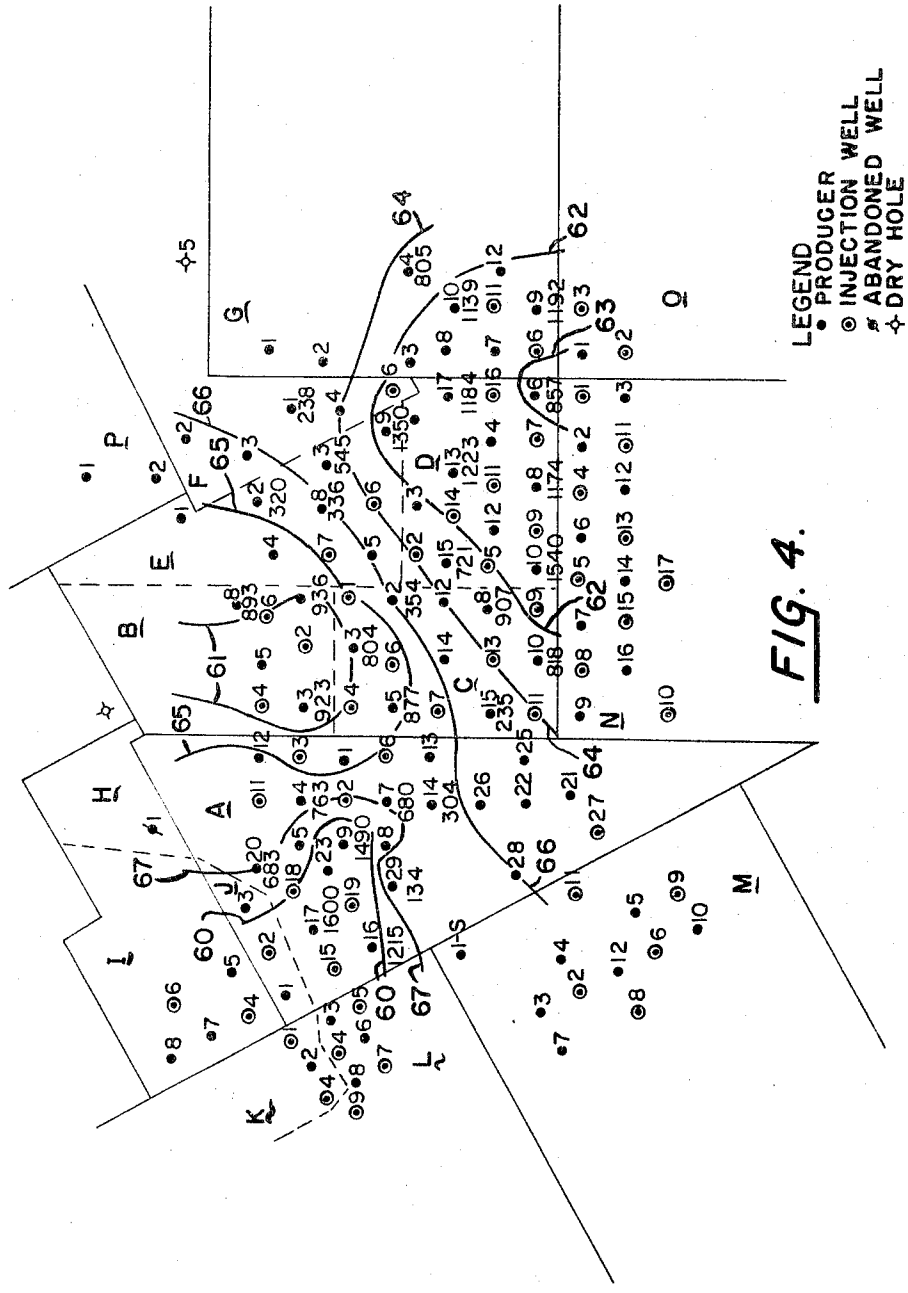


FIG. 4.

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METHOD OF DETERMINING THE OIL AVAILABILITY CONTOUR OF AN OIL FIELD

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16 Claims. (Cl. 166—4)

This invention relates to oil recovery and more particularly to the determination of the "oil column" in oil and gas reservoirs. As used herein, the term "oil column" means the oil availability contour or those areas between wells in which the production of oil, particularly through secondary recovery operations, is most likely to be successful. This invention also contemplates the conduct of secondary recovery operations in accordance with the determination of the oil column made in accordance therewith.

In the production of oil from geological strata beneath the ground, there is the possibility of both primary production and secondary production. Primary production is the production of oil when the oil flows naturally from the well, as through gas or water drive, or oil collects in the well or wells in sufficient amount to be pumped therefrom. Secondary recovery operations are those in which an externally supplied impetus is given to the travel of the oil through the formation to the production well or wells. The importance of secondary recovery operations is evident from the widely accepted theory that primary production operations will leave from 60% to 75% of the oil in the strata, while secondary recovery operations will increase the recovery to from 75% to 90% of the oil in the strata, leaving 10% to 25% of the oil in the strata.

The most common type of secondary recovery operation is that of water flooding, in which water under pressure, in some instances as low as around 150 pounds per square inch but sometimes as high as several thousand pounds per square inch, is pumped down injection wells, in order to force the oil in the producing formation to the production wells, from which it is usually pumped. It is normally uneconomical to pump oil from a production well unless the level of the oil rises in the well to a height such that the pump itself may be located in the well at an economical distance below the surface. Although the rise of oil in a well might be referred to as an oil column, the term as so used should not be confused with the term "oil column" having the meaning used herein, as defined above.

The usual spacing of the wells in a proven oil field is a rectangular spacing, in which each well is placed at the center of a predetermined area, such as an area of ten acres. A widely used system of injection and production wells is what is termed a "five spot," in which alternate wells in both north-south and east-west rows (assuming that the rows of wells in a rectangular configuration are so oriented with respect to the compass) is a production well and alternate wells are injection wells. This produces a pattern in which each production well is surrounded by four injection wells, at the four corners of a rectangle at the center of which is the production well. Of course, each of the injection wells for any production well, in this five spot pattern, will also surround other production wells. Other positions of the injection and production wells have been utilized, such as a hexagonal pattern of injection wells surrounding each production well. When the plane of the strata is horizontal or not too far therefrom, it is theoretically desirable to apply water pressure to the strata from each of the injection wells simultaneously. However, this is not always possible, since the information upon which a secondary recovery operation is based is often not nearly as extensive as would be desired; thus, at times, six injection wells, surrounding two

production wells to provide two five spot patterns, are initially utilized, and, if this operation is successful, other injection wells are added. Generally speaking, a good production well also makes a good injection well, since if the porosity and other attributes of the formation are such that oil will sufficiently readily flow to a production well, then water can be used successfully to drive the oil through the strata to a production well. Similarly, if the porosity and other attributes of the strata are such that oil will not successfully flow to a production well, then water will not be successful, from an economical standpoint, in forcing the oil from that well to an adjacent production well. Other types of water flooding include those in which injection wells spaced along the lower edge of a strata inclined to the horizontal are first utilized, then the injection moved upwardly along the strata as the oil is produced. Generally speaking, a movement up the strata of the injection wells will be determined by the time when an uneconomical amount of water is pumped from the producing wells. For a small field, the injection well pattern may be selected to extend around the periphery of the field, so that the water introduced to the injection wells will drive the oil inwardly through the formation into the production wells. There are, of course, numerous other types of patterns which may be followed in secondary recovery operations, particularly using water flooding. Another type of secondary operation comprises pressurizing by gas, particularly when geological information indicates that the oil production is through a so-called gas drive, rather than a water drive. However, the great majority of secondary recovery operations involve the use of water to provide a force to move the oil in the formation to the production wells.

In general, as low a water pressure as will produce a recovery of oil at the production wells is utilized at the injection wells, since the higher the water pressure, the greater the tendency for so-called "channeling," i.e. for the water to find the path of least resistance and follow or open up channels to a production well, so that the oil around the channels will not be driven to the production well. Thus, in any secondary recovery operation, the water pressure utilized should be correlated with the permeability of the formation. In some instances, pressures as low as 150 pounds per square inch can be utilized, while with formations having considerably less permeability, higher pressures must be utilized. For instance, in one area, the pressure of water supplied to the injection wells was maintained at around 1000 pounds per square inch for about three and one-half years, then increased to 1250 pounds per square inch. The vertical point at which water is introduced to the injection wells may also be changed, since it is desirable that the oil be forced toward the producing wells, from the top to the bottom of the producing zone.

The petroleum engineer needs all of the information which can be gleaned and usually wants much more, in order to make a prediction as to the economic feasibility of any contemplated secondary recovery operation. After a field has been in production, there are ordinarily no records of the production of each specific well, although these may be helpful if they exist. While electric logs, gamma ray logs, neutron logs or the like can be run on any desired well, they do not always provide as much information as desired, as well as being quite expensive. Also, while discovery or so-called "wildcat" wells are often logged for gas, i.e., either the gas which separates from the mud used in drilling the well or from the cuttings borne by the mud to the top of the well, or both, such logs are not ordinarily obtained when wells are being drilled in a proven production area. While cores or samples of the strata being drilled through are more usually secured while drilling a discovery well, core sam-

ples are often taken when wells are being drilled to exploit an established field. Thus, there are usually a sufficient number of cores on hand, so that the dip and strike of a producing formation may be determined, as well as whether the field was originally actuated by gas drive or water drive. In addition, the cores will show the lithology of the producing formation, as well as giving some indication of the porosity and permeability. However, the cores normally represent the conditions of the field at the time of drilling, which, in some instances, may be several years in the past. Thus, it is highly desirable to provide the geologist or petroleum engineer with as much information as possible, when attempting to determine the economic feasibility of a secondary recovery operation.

Among the objects of this invention are to provide a novel method of determining the oil column or oil availability contour of an oil field; to provide a method of operating secondary recovery operations, in order to utilize the wells most likely to produce a sufficient amount of oil to render the operation economically feasible; to provide such methods which may be readily applied to all of the wells in a given area, irrespective of how long the wells have been in production; to provide a method of determining the further use of a secondary recovery operation, even several years after the initial start thereof; to provide a method of testing the operation of a secondary recovery operation; to provide a method of determining the relative rate of flow of the injection water to various wells; to provide such methods which do not require the installation of additional equipment at the normal well; and to provide such methods which may be carried out quickly and economically.

The present invention is based upon the unexpected discovery that, irrespective of the amount of oil being produced or the amount of gas separating from that oil, there is a definite correlation between the oil column or the oil availability contour and the ratio or proportion between heavier gases, such as isobutane, normal butane, isoheptane and normal heptane, or even the hextanes, and the lighter gases, including methane, ethane and propane, separating from the oil at any particular well. The manner in which advantage is preferably taken of this unexpected discovery, as well as the novel features of this invention, will become apparent from the description which follows, taken in conjunction with the accompanying drawings, in which:

FIG. 1 is a side elevation of a portion of the piping and valves at the top of a production well;

FIG. 2 is a top plan view of equipment for collecting gas samples, to be used in carrying out the method of this invention;

FIG. 3 is a reproduction of a chromatographic chart produced when gas produced from an oil well was tested in accordance with this invention; and

FIG. 4 is a diagram showing lease and well locations in a field in which secondary operations have been carried out and to which the principles of this invention have been applied.

In accordance with this invention, the gas separating in a well from the oil beneath, such as between the pumping tube and the casing, is tested for gases including methane, ethane, isopropane, normal propane, isobutane, normal butane, isopentane and normal pentane, as well as for isohexane and hexane, if desired. The total of the relative proportions, such as percentages, of the lighter gases, including methane, ethane and propane, are then determined, as well as the relative proportions or percentages of the heavier gases, including isobutane, normal butane, isopentane and normal pentane, as well as isohexane and normal hexane, if desired. In general, the higher the total percentage of the heavier gases, the higher the production which may be expected from such a well, although the total percentage of the lighter gases may be used as an inverse indication, i.e., the lower the total

percentage of the lighter gases, the better production may be expected from such well. A plan of the oil field may be utilized in determining the areas of probable best and poorest production, as well as areas of probable intermediate production. As indicated above, the wells which are to be utilized as injection wells are normally among those which are indicated to be the best producing wells, while the area of the field in which the poorest production wells are located may be omitted from the secondary recovery operation, or deleted from a secondary recovery operation which is already in use. Thus, the method of this invention comprises the recovery, from a plurality of wells in an oil field tapping an oil reservoir, of occluded gases from each well, determining the relative amounts of such occluded gases from each well separately for a plurality of hydrocarbon gases, including methane, ethane, propane, isobutane, normal butane, isopentane and normal pentane, and determining the total relative proportions of the heavier gases, including isobutane, normal butane, isopentane and normal pentane, for each such well. The method of this invention also comprises the above steps and, in addition thereto, determining the use of wells for secondary recovery operations on the basis of the utilization of those wells having such a relative proportion greater than a predetermined value. The method of this invention may further comprise the above steps and, in addition thereto, the plotting of the total relative proportions of the total of such heavier gases on a map or plat of the field or reservoir area, or the inverse, i.e., the total relative proportions of the lighter gases.

In carrying out the method of this invention, samples of the occluded gases separating from the oil in each such well are taken and may be tested at the general location of the field or taken to a laboratory for testing. The determination of the relative percentages of such gases in each sample may be made at a laboratory, as by cryogenic apparatus or other apparatus particularly adapted to analyze samples of hydrocarbon gases. The apparatus best suited for this purpose is chromatographic apparatus, in which a sample of gas, often diluted with helium, is passed through an elongated column, normally tubing wound in a spiral to reduce the total length of the column and packed with a hydrocarbon gas absorbent material. The more usual materials used for such packing include silica gel, aqua regia treated fire brick, "Chromasorb" or the like, in finely divided form, such as 30 to 60 mesh, and carrying a small percentage, such as between 10% and 20%, of a preferential gas absorbent liquid, such as propylene carbonate, dimethyl sulfolane, diisopropyl phthalate, diisodecyl phthalate, specially treated silicones or the like, although dibutyl phthalate or hexadecane may be found to be preferable. Two columns, in series, containing a different absorption material, may also be utilized. A small sample of the gas to be tested, such as 2 cc., normally diluted with helium, is passed into the absorption column, with the gas or gases which are discharged from the absorption column being passed through a detector, such as a thermal conductivity measuring cell, or other type of electrical detection device which will produce a current in proportion to the amount of a particular gas. In the absorption column, the heavier gases are preferentially absorbed, so that the lightest gas, i.e., methane, passes first from the column to the detector. A short interval of time later, the next heavier gas, i.e., ethane, will pass to the detector, then propane, and so on. Preferably, a record is made of the current produced by the detector, so that the relative amounts of the particular gases detected will be indicated on a chart. The values of the relative amounts of the gases detected are then read from the chart and the total proportions of the heavier gases and the lighter gases are then determined. By comparing the total amount of heavier gases detected with the total amount of gasses detected, the percentage of the heavier gases may be determined, and this percentage is used in determining

whether a particular well or series of adjacent wells are probably oil producing wells for secondary recovery operations. The chromatograph is now a generally recognized instrument for gas analysis, such as the Perkin-Elmer Model 810 or Model 820 gas chromatograph, while the procedures outlined in the standards set for chromatographic gas testing by the American Society of Testing Materials, the National Gasoline Association of America or the California Natural Gas Association may be followed. The recorders are also standard instruments, there being several makes available which are suitable, such as the Leeds and Northrup Model H.

Since the testing of the samples may be done by the same chromatographic apparatus and the reuslts placed on charts produced by the same recorder, only one such apparatus is usually necessary. Also, the chromatographic apparatus is sufficiently small, as compared with cryogenic testing apparatus, for instance, that it may be transported to the oil field, as in a trailer. Each sample may be tested in a matter of minutes, so that the testing procedure may be accomplished relatively quickly. Furthermore, the collection of the gas samples requires a minimum of additional equipment not usually found at the normal oil well.

As illustrated in FIG. 1, a more usual oil production well, which is being pumped, is provided with a casing **10** which extends down into the well and a pump tube **11** which also extends down into the well inside the casing **10**, with a space between the casing **10** and pump tube **11** in which occluded gases can and normally do separate from the oil in the well. The pump is usually of the reciprocating type and is operated by a pump rod **12** which extends within the pump tube **11**. At the top of the well, the casing terminates in a collar or cross **13**, provided with a packing gland **14**, while a nipple **11'** forms a continuation of the pump tube **11**, connecting collar **13** to a cross **15**. The cross **15** is also provided with a packing gland **16** for the pump rod **12**, while the oil pumped upwardly through the pump tube **11** is discharged through a production line **17**, normally having a check valve **18** and a shut-off valve **19** therein. The production line **17** may also be provided with a T **20**, shown as having a plug **21** therein, for connection of an alternate discharge line, or for any other desired purpose. A bleed line **23** is connected to the opposite side of cross **15** and is provided with a valve **24**, for removal of oil for sampling purposes, release of separated gases in the line, or the like. Bleed line **23** is preferably arranged so as to discharge into a funnel **25** connected with a return line **26** leading to one side of collar **13** and provided with a shut-off or regulating valve **27**. Return line **26** may be used ot return oil to the well during sampling, or to vent gases separating from the oil and collecting between casing **10** and pump tube **11**, particularly in the case of a well used in water flooding operations, since a high back pressure of gas in a production well is undesirable, inasmuch as such a back pressure tends to decrease the amount of oil which can be forced through the strata from the injection wells to a production well.

The opposite side of collar **13** is provided with a threaded aperture in which a so-called bull plug is normally placed, although this connection may be utilized for the removal of gas when gas is being produced in an amount sufficient to warrant the recovery thereof. For taking samples in order to carry out the method of this invention, such a bull plug is replaced by a nipple **29** connected to a valve **30** from which a sample tube **31** conveys the gas being sampled to the collection equipment shown in FIG. 2.

As in FIG. 2, the gas sample tube **31** is connected to a valve **32**, in turn connected to one end of a cross **33**, the opposite end of which is connected by a nipple **34** with a valve **35** connected to one end of a gas sample container **36**, having at the opposite end a valve **37** provided with a boss **38** in which is installed a frangible disc, to prevent the pressure of gas in container **36** from rupturing the same if the pressure should become too high. In general, the container **36** may be a fabricated, stainless steel container having a capacity of from approximately 300 milliliters to 1000 milliliters and a pressure rating of from 300 to 3000 pounds per square inch. Each of the valves **35** and **37** are conveniently needle type valves provided with an attached plug **39** for plugging the ends of the valves when desired.

As will be evident, it will be necessary to have a series of containers **36**, depending upon the number of samples which are to be taken and particularly the nearness of the analytical apparatus. Also, it will be desirable to have a number of sets of the remaining parts of the equipment shown in FIG. 2, to permit a number of samples to be taken at different wells simultaneously. Also, it will be desirable to have as many nipples **29** and valves **30** as the number of wells to be tested over a period of one or two days, since prior to taking the samples, each well is preferably shut in for a period of around 24 hours, by closing valves **19**, **24** and **27**, to permit gas to collect in the space between casing **10** and pump tube **11**. Of course, before the well is shut in, a valve **30** should preferably be connected to the collar **13** and closed.

The equipment shown in FIG. 2 may also include a T **41** connected to one side of cross **33** and also connected to each of valves **42** and **43**. Valve **42** may be connected by tubing **44** with a vacuum pump, when the equipment shown in FIG. 2 is to be evacuated, as for the introduction of a lighter gas, such as helium, through valve **43**. A valve **45** may be connected to the opposite side of cross **33**, from which a tube **46** leads to a pressure gauge or manometer.

If the gas sample is to be transported for any great distance, the container **36**, along with valves **35** and **37**, may be utilized for that purpose by connecting tubing **31** to valve **35**. After the sample is taken, the ends of valves **35** and **37** are closed by plugs **39**. However, if the chromatographic gas analysis apparatus is located in a trailer which is comparatively close to the well, the equipment may be disconnected by disconnecting tube **31** from valve **32**. Thus, the valves **42**, **43** and **45** and parts connected therewith are adapted for use with chromatographic gas analysis apparatus.

In taking the sample, the valves **30** of FIG. 1 and **32** of FIG. 2 are opened, as well as valves **35** and **37**, to permit gas from the well to flow through the container, to permit a sample of gas to displace any gases within the container and valves associated therewith. Then the outermost valve, i.e., valve **37**, is closed, after which valve **35** is closed, then valve **30** at the well closed and the container, its associated piping and valves disconnected from the well by disconnecting tube **31** from valve **32**. When the container is brought to the analysis apparatus and is to be connected thereto, a carrier gas, such as helium, may be introduced through valve **43** and the sample allowed to flow to the apparatus from valve **37**, by which it is connected thereto.

Preferably, several samples are taken from each well, such as three, so that an average or mean of three or more analyses may be taken as more truly representative of the values obtained.

The record made of the three tests of one of the wells shown in FIG. 4 is reproduced in FIG. 3, which shows a portion of a chart **48** having a number of transverse lines **49**, representing time, and longitudinal lines **50**, representing amplitude of the readings. It will be noted that the chart width represents fifty units, of which the longitudinal lines **50** represent five each, although the actual chart is provided with fifty longitudinal lines **50** to permit the maximum value of the curves **51** through **57** to be determined more easily, as well as a greater number of transverse lines **49**, the number of lines **49** and **50** shown being reduced for clarity of illustration. Thus,

the curves or lines on the chart produced by the recorder pen include a movement of the pen, indicated by each "kick" or curve **51** representing methane separated in the gas absorption column and passing through the detector, with the curves **52** representing ethane separating a very short time later and passing from the absorption column to the detector, for each of the three samples. The usual recorder is provided with a switch so that the movement of the pen may be reduced by one-half, one-quarter, one-eighth or one-sixteenth of the normal movement of the pen, to permit larger swings or movements of the pen to be reproduced on the chart. Thus, as indicated with respect to the curves **51** and **52**, the readings thereof on the chart are multiplied by sixteen to obtain the actual values of the impulse received by the recorder. Similarly, the curves **53**, which represent propane, released by the absorption column and travelling through the detector, for each of the three samples, are multiplied by eight. Also, the curves **54** and **55**, representing isobutane and normal butane, respectively, represent the relative amounts of these gases released from the absorption column and passing through the recorder, the value thereof being multiplied by two. The curves **56** represent isopentane and the curves **57** represent normal pentane, for each of the three samples, released at later times from the absorption column and passing through the detector, but require no multiplying factor, since the amplitude of these curves is such that they do not require more than one width of the chart.

It will be noted that several of the curves, such as **53** through **57**, have a relatively broad base, in which instance the average or mean value of the peak of the curves may be taken as accurately reflecting the relative proportion of the gases involved. However, the curves **51** and **52** have a relatively narrow base, caused by the fact that the ethane is released from the absorption column a much shorter time after the methane, than, for instance, is normal pentane after isopentane. In the case of the curves **51** and **52**, a value higher than the mean or average, such as the maximum peak value of the curves **51** and **52**, is taken as the reading, to compensate for the apparent overlapping of these curves, i.e., all of the methane had not passed through the recorder before ethane began to flow through. Subject to this type of correction, the peak values may be taken as representative of the quantitative amounts of the respective gases, so that a planimeter or other device for measuring area need not be used for the curves.

The actual values determined from that portion of the chart reproduced in FIG. 3, which represent the samples taken from well No. 3 in lease area C of FIG. 4, are as follows, where M represents methane, E represents ethane, P represents propane, IB represents isobutane, NB represents normal butane, IP represents isopentane and NP represents normal pentane:

TABLE I

	M	E	P	IB	NB	IP	NP
Reading	1,504	432	456	64	118	17	10
Mol percent	4.1	1.1	1.7	.35	.80	.17	.10
Percent	57.82	16.61	17.53	2.46	4.54	0.65	0.39

It will be noted in the above Table I that the total of the readings for the various gases is 2601 and that the percentages of the respective gases are based on this total. Also, the mol percentages, in the second line of the above table, are based upon the readings divided by a factor based on the molecular weight of the particular gases involved. In the following Table II, the total of the readings for methane and ethane, i.e., C_1 and C_2, the reading for propane, i.e., C_3, and the total of the readings of the heavier gases, i.e., C_4 and C_5, together with the percentages thereof, are shown:

TABLE II

	Total	Percent
C_1 and C_2	1,936	74.43
C_3	456	17.33
C_4 and C_5	209	8.04
Totals	2,601	100.0

It will be noted that the percentage of the heavier gases for this particular well is 8.04%. When multiplied by 100, this percentage gives a value of 804, which is the value shown in FIG. 4 for well No. 3 in lease area C.

The following Table III similarly relates to well No. 3 in lease area B of FIG. 4, and corresponds to both Table I and Table II:

TABLE III

	M	E	P	IB	NB	IP	NP
Reading	1,440	700	750	92	168	22	12
Mol percent	4.0	1.7	2.7	.50	1.1	.22	.12
Percent	45.25	21.96	23.56	2.85	5.30	0.69	0.37

	Total	Percent
C_1 and C_2	2,140	67.21
C_3	750	23.56
C_4 and C_5	294	9.23
Totals	3,184	100.00

The following Table IV similarly relates to well No. 10 in lease area G of FIG. 4 and again corresponds to both Table I and Table II:

TABLE IV

	M	E	P	IB	NB	IP	NP
Reading	1,440	640	672	100	200	33	21
Mol percent	3.8	1.6	2.3	.53	1.2	.33	.20
Percent	46.36	20.61	21.64	3.22	6.44	1.06	.68

	Total	Percent
C_1 and C_2	2,080	66.97
C_3	672	21.64
C_4 and C_5	354	11.39
Totals	3,016	100.00

It will be noted from Table III that the total percentage of C_4 and C_5 is 9.23%, which, when multiplied by 100, gives a value of 923, which is the value shown in FIG. 4 for well No. 3 in lease area B. Similarly, the total of C_4 and C_5, from Table IV, is 11.39% which, when multiplied by 100, gives a value of 1139, which is the value shown in FIG. 4 for well No. 10 in lease area G.

The following Table V similarly relates to well No. 29 in lease area A of FIG. 4:

TABLE V

	M	E	P	IB	NB	IP	NP
Reading	1,336	144	64	6	8	4	3
Percent	85.34	9.24	4.08	0.38	0.52	0.25	0.19

	Total	Percent
C_1 and C_2	1,468	94.58
C_3	64	4.08
C_4 and C_5	21	1.34
Totals	1,565	100.00

It will be noted from Table V that the total percentage of C_4 and C_5 is 1.34% which, when multiplied by 100, gives a value of 134, which is the value shown in FIG. 4 for well No. 29 in lease area A. It will also be noted that, not only is the percentage of C_4 and C_5 very low, as compared with the wells on which Tables I through IV are based, but also that the ratio of butane to propane is considerably lower than for the wells on which Tables I through IV are based.

As shown in FIG. 4, the total percentages of the heavier gases, such as C_4 and C_5, may be plotted on a plat of an oil field, some or all of the wells of which have been tested. In general, the principal purpose of plotting the values is to determine those areas of the oil field which contain wells which are most likely to be wells providing an adequate production rate, for secondary recovery operations. Also, the areas of the oil field which are least likely to provide adequate production and the areas intermediate the least likely and the most likely areas of production can also be determined. From this determination, for a comparison of the total percentage value of the higher gases, i.e., C_4 and C_5, or also including C_6, i.e., isohexane and normal hexane, if desired, the secondary recovery operation may be carried out in order to provide the maximum possible recovery, consonant with economical operation, utilizing preferably those wells in the areas of most likely production, or also intermediate likelihood of production, and eliminating, as far as practicable, the least likely areas of production.

The method of this invention may also be applied to oil fields in which secondary recovery operations have been carried out or are being carried out, in order to determine whether any areas of the field should be eliminated from the secondary recovery operations, or whether certain areas should be concentrated on in preference to others. In FIG. 4, the lease areas A through P, inclusive, the boundaries of which are indicated by either solid or dotted lines, represent the areas of different leases in an oil field located in Pecos County, Tex. The areas A through G, inclusive, belong to one owner, on which the method of this invention was carried out, with the remaining lease areas H to P either belonging to other owners or representing areas in which the method of this invention is yet to be carried out. As will be evident, the plat of FIG. 4 represents a field in which secondary recovery operations are being carried out, the producing wells and injection wells being identified by the symbols shown on the legend accompanying FIG. 4. The well number, in each lease area, is placed at the right of each well, while the total percentage of C_4 and C_5, multiplied by 100, is placed below each of the wells tested. It will be observed that, of course, only producing wells were tested. Although the line of demarcation is somewhat arbitrary, being variable upwardly or downwardly for any particular field, the figures of 900 and above, representing a percentage of C_4 and C_5 of 9% or greater, were selected as representing the wells located in the area most likely to provide adequate production, with those wells in the area represented by figures between 600 and 900, i.e., over 6% but less than 9% as a total percentage of C_4 and C_5, as wells in an intermediate area. Thus, the wells having a figure of 600 or less are located in areas having the least likelihood of adequate production. It will be noted that the line **60** is drawn around an area in which the wells have readings in excess of 1200 and therefore indicate that secondary recovery operations should be continued in this area, while the line **61** is drawn around an area in which the wells have readings of 900 or above, again indicating an area of greater likelihood of production. Similarly, the line **62** is drawn around an area in which the wells have readings above 1100, with line **63** separating out an area in which the well has a reading of slightly less than 900. Thus, the area between lines **62** and **63** is an area which should be continued in production. The line **64** is drawn around an area surrounding that enclosed by line **62**, in which the readings of the wells are between 600 and 900, being an area of intermediate possibility of production. Similarly, the line **65** is drawn around an area, surrounding that enclosed by line **61**, in which the wells have readings of between 600 and 900, again indicating an area of intermediate likelihood of production. Line **66** is drawn through approximately the center of a low oil recovery potential area, in which further operations will probably be uneconomical. Line **67** is drawn to connect areas of wells having readings in the 600 to 700 range and it will be noted that it closely approaches line **60** in the area of well **29** of lease area A, which is a well having a high gas column and low recovery potential. This indicates a permeability barrier. As will be evident, the contour lines **60** to **67**, inclusive, indicate the contour of the oil column, i.e., the oil availability contour, of the field. This information is, of course, quite valuable to the petroleum engineer in charge of the secondary recovery operations involved.

The conclusions reached from a study of the oil availability contours of FIG. 4 are that maximum effort should be concentrated in lease area D, which appears to be the area of greatset potential oil recovery. Also, in lease area B and the adjacent portion of lease area C, production could be stimulated so that the wells would take more injection water. In lease area A, around wells Nos. 17 and 23, a study should be made to determine the flow of injection water. While a good recovery area, from the oil availability contours, the permeability barrier indicated by the closeness of line **67** to line **60** in the area of well 29 of lease area A, further indicates that fracturing or acidizing may be necessary.

As will be evident, the oil column or oil availability contour of a field may be plotted in a similar manner for a field in which secondary recovery operations are contemplated, not only to indicate the areas in which secondary recovery operations should be established, but also those areas in which the secondary recovery operations should not be established. Again, the oil column or oil availability contour of the field is of real advantage to a petroleum engineer who is preparing a report on the potential of the proposed secondary recovery operations.

In addition to plotting, on a plat of the field, the relative proportions or percentages of the heavier gases, such as C_4 and C_5, or also C_6, if desired, to determine the oil column or oil availability contour, which may also be effected by using the inverse or total percentages of the lighter gases, i.e., C_1 through C_3, other contour lines may be drawn on other plats of the same field, in order to secure an indication of both the highest and lowest gas columns in the field and also the gas to oil contact points. Thus, on one plat of the well locations, the methane readings from the analyses of the gases obtained at the wells, when placed on a plat of the well locations, will provide the information necessary to draw contour intervals indicating the highest and lowest gas columns in the field i.e., one form of correlation of the relative amounts

of methane with the geographical location of the wells. The readings based on either mol percentage or relative percentage may be utilized for the methane readings. Or, for somewhat greater accuracy, the ratio of methane or C_1 to butane or C_4 may be calculated for each of the wells and these values placed on a plat of the field. Contour lines may be drawn to indicate the highest and lowest gas columns in the field, it being noted that the higher the proportion of methane to butane, the higher the gas to oil ratio, with a corresponding greater gas column and lower oil recovery potential.

The proportion or ratio of propane or C_3 to butane or C_4 may also be calculated for each of the wells tested and these values placed on another plat of the well locations, in order to draw contour lines which will indicate the gas to oil contact points. When drawing the contour intervals based on the propane to butane ratios, lines may be drawn around areas in which the ratio of propane to butane is two or greater, these lines indicating the gas to oil contact points. As will be evident from Tables I to V, the methane and propane readings normally do not bear the same ratio to the total of the heavier gases for any particular well.

In further accordance with this invention, the rate of flow of the oil or injected water, between one or more injection wells and one or more production wells, may be determined. It will be realized, of course, that it may require a year or more to make such a determination, since it may require that much time for the identifying material to travel from the injection well to the adjacent production wells. In accordance therewith, a known gas, which would not normally find its way through the formation, is used as an identifying element, a sudden increase in the amount or relative percentage of this gas, separating from the occluded gases at the production well, being indicative of the time of travel of the injection water from the injection well to the production well. A suitable gas for this purpose is normal butane, which has little tendency to travel by itself through the formation, as do the lighter gases, i.e., methane, ethane and propane, but an increase of which is detectable at any production well. The use of normal butane as an identifying element has further advantages, in that, when the wells of the field are being tested for an indication of productivity, in accordance with this invention, the reading or percentage of normal butane, through a comparison of the percentage of normal butane with the percentage of other gases, as compared with the ratio of such percentage for the last previous test, will give an indication of a sudden increase in the amount of normal butane, due to the butane injected with the water at the injection well reaching the production well. Thus, the wells in a field in which butane is injected, along with the water, may be tested at shorter periods of time, such as three or four months between each test, so that an indication of the travel time of the injection water may be found. It will be understood, of course, that the actual travel time, as so indicated, should be correlated with the known data regarding the field, including the porosity and permeability of the formation, as far as known from cores. Thus, when the identifying butane reaches a production well in a much shorter time than would be expected from the known data, preventive measures can be taken, such as by reducing the pressure of the water in the injection wells, to reduce or avoid the possibility of channeling, i.e., the injection water producing comparatively large channels in the formation through which the water travels without forcing any oil ahead of it. It will be understood, of course, that the normal butane need not be pure; that is, the injected gas may include isobutane or other heavier hydrocarbon gases, in addition to normal butane, as well as small amounts of lighter hydrocarbon gases or other gases.

From the foregoing, it will be evident that the method of this invention fulfills to a marked degree the objects and requirements hereinbefore set forth. The method of this invention, through the analysis of gases which separate from the oil in a plurality of wells, provides extremely valuable information on which a proposed or potential secondary recovery operation may be based, or secondary recovery operations, already in use, continued. The analysis of the gases obtained from the wells is very readily carried out, particularly with chromatographic apparatus, while the desired total relative proportion or percentage of the heavier gases is readily obtained. As indicated, either the heavier gases C_4 and C_5, or C_4 through C_6, may be utilized in carrying out the method. As will also be evident, when the readings indicative of the probable production rate of the wells is placed on a plat of the field, contours may be drawn which indicate the oil column or oil availability contour of the field. Thus, this invention is of great advantage to the petroleum engineer who is determining either the feasibility of secondary recovery operations for a particular field, or the desirability of the continuation of all or a portion of secondary recovery operations already in use. As will be evident, this additional information relative to the field and particularly the individual wells therein, is of great value for use in a more complete evaluation of producing oil properties and the evaluation of wells in areas with respect to suitability for water flooding injection. Thus, wells which will probably never be effective can be abandoned in an old water flood project, so that equipment can be salvaged and operating costs reduced. Also, wells which will probably never be effective can be eliminated from a proposed water flood project, so that equipment and operating costs for those wells can be saved, while the necessary time and effort can be expended upon those wells which are more likely to be effective in production.

For the most effective results, the method of this invention can be applied to a secondary recovery operation, particularly a water flooding project, on a periodic basis, so that any changes in the oil column can be detected. In addition, the rate of travel of the injection water can be determined through placement of an identifying material in the injection water, particularly one which will be detected when periodic analyses are made. As indicated, normal butane is an excellent indicator for this purpose. Thus, channeling or other adverse effects can be detected at a relatively early date and preventive measures can be taken if the flow rate is unduly high. Finally, an increased recovery factor should be realizd from a water flood or secondary recovery operation, when the additional knowledge of the oil field beneath, provided by the method of this invention, is secured.

Although a preferred manner of carrying out the method of this invention has been described, it will be understood that variations may be made therein, without departing from the spirit and scope of this invention.

What is claimed is:

1. A method of determining the oil column gradient of an oil reservoir from which oil is removed through wells, which comprises recovering occluded gases separating from oil in a plurality of such wells; testing such removal gases to determine the relative amounts in such removed gases, for each well separately, of a plurality of hydrocarbon gases, including methane, ethane, propane, isobutane, normal butane, isopentane and normal pentane; determining the sum of the relative proportion of the heavier gases, including isobutane, normal butane, isopentane and normal pentane, in such removed gases, for each such well; and correlating such sums of relative proportions with the geographical location of said wells to determine those areas in which such wells have such sums of relative proportions greater and less than at least one predetermined value.

2. A method as defined in claim 1, wherein said heavier gases include isohexane and hexane.

3. A method as defined in claim 1, which includes plotting the relative proportions of such sums of said heavier gases on a plat of the location of such wells.

4. A method as defined in claim 3, which includes placing on said plat lines indicating those areas in which are located wells having such a relative proportion sum greater than a first predetermined value; lines indicating those areas in which are located wells having such a relative proportion sum lower than said first but greater than a second predetermined value; and lines indicating those areas in which are located wells having such a relative proportion sum less than said second predetermined value.

5. A method of conducting secondary recovery operations for an oil reservoir from which oil is obtainable through wells, which comprises recovering occluded gases separating from oil in a plurality of said wells; separately determining the relative proportion of such gases for each said well of the sum of the heavier gases including isobutane, normal butane, isopentane and normal pentane in comparison with the total amount of hydrocarbon gases therein, including methane, ethane and propane; conducting the secondary recovery operation in substantially those areas containing wells having such relative proportion greater than a predetrmined value; and eliminating from the secondary recovery operation substantially those areas containing wells having such relative proportion less than said predetermined value.

6. A method as defined in claim 5, wherein said heavier gases include isohexane and normal hexane.

7. A method of conducting secondary recovery operations for an oil reservoir from which oil is removable through production wells to which oil tends to be driven by injection fluid introduced under pressure into injection wells adjacent said production wells, which comprises periodically recovering occluded gases separating from oil in a plurality of said production wells; testing to determine the relative amounts, in such removed gases and for each well separately, of hydrocarbon gases including methane, ethane, propane, isobutane, normal butane, isopentane and normal pentane; and determining the oil availability contour of said reservoir from the sum of the proportions of the heavier gases, including the butanes and pentanes, to the total gases, including said heavier gases and the lighter gases, methane, ethane and propane.

8. A method as defined in claim 7, which includes introducing butane with the injection fluid in selected injection wells; and determining the rate of flow of said injection fluid by increases in the proportion of butane in the gases from production wells adjacent such injection wells.

9. A method of determining the apparent rate of flow of injection fluid in an oil reservoir from which oil is recovered through production wells to which oil tends to be driven by injection fluid introduced under pressure into injection wells adjacent said production wells, which comprises introducing butane with the injection fluid in selected injection wells; periodically recovering occluded gases separating from oil in a plurality of production wells adjacent such injection wells; and testing to determine the relative proportion of butane, in comparison with the total amount of gases from methane through at least the pentanes, whereby an indication of the rate of travel of the injection fluid from one of such injection wells to an adjacent production well may be obtained from a relatively sudden increase in the proportion of butane.

10. A method of determining the oil column gradient of an oil reservoir from which oil is removed through wells, which comprises recovering occluded gases separating from oil in a plurality of such wells; testing such removed gases to determine the relative amounts in such removed gases, for each well separately, of a plurality of hydrocarbon gases, including methane, ethane, propane, isobutane, normal butane, isopentane and normal pentane; determining the sum of the relative proportion of the heavier gases, including isobutane, normal butane, isopentane and normal pentane, in such removed gases, for each such well; plotting the relative proportions of such sums of said heavier gases on a plat of the location of such wells; and placing on a plat of said field the relative proportions of methane for each of said wells so tested, in order to obtain an indication of the highest and lowest gas columns in said field.

11. A method of determining the oil column gradient of an oil reservoir from which oil is removed through wells, which comprises recovering occluded gases separating from oil in a plurality of such wells; testing such removed gases to determine the relative amounts in such removed gases, for each well separately, of a plurality of hydrocarbon gases, including methane, ethane, propane, isobutane, normal butane, isopentane and normal pentane; determining the sum of the relative proportion of the heavier gases, including isobutane, normal butane, isopentane and normal pentane, in such removed gases, for each such well; plotting the relative proportions of such sums of said heavier gases on a plat of the location of such wells; determining the proportion of methane to butane for each such well; and placing on a plat of said field the values of such proportion for each such well, in order to obtain an indication of the highest and lowest gas columns in said field.

12. A method of determining the oil column gradient of an oil reservoir from which oil is removed through wells, which comprises recovering occluded gases separating from oil in a plurality of such wells; testing such removed gases to determine the relative amounts in such removed gases, for each well separately, of a plurality of hydrocarbon gases, including methane, ethane, propane, isobutane, normal butane, isopentane and normal pentane; determining the sum of the relative proportion of the heavier gases, including isobutane, normal butane, isopentane and normal pentane, in such removed gases, for each such well; plotting the relative proportions of such sums of said heavier gases on a plat of the location of such wells; and placing on a plat of said field the relative proportions of propane for each of said wells so tested, in order to obtain an indication of the gas to oil contact points.

13. A method of determining the oil column gradient of an oil reservoir from which oil is removed through wells, which comprises recovering occluded gases separating from oil in a plurality of such wells; testing such removed gases to determine the relative amounts in such removed gases, for each well separately, of a plurality of hydrocarbon gases, including methane, ethane, propane, isobutane, normal butane, isopentane and normal pentane; determining the sum of the relative proportion of the heavier gases, including isobutane, normal butane, isopentane and normal pentane, in such removed gases, for each such well; plotting the relative proportions of such sums of said heavier gases on a plat of the location of such wells; determining the proportion of propane to butane for each such well; and placing on a plat of said field the value of such proportion for each such well, in order to obtain an indication of the gas to oil contact points.

14. A method of obtaining an indication of the highest and lowest gas columns in an oil reservoir from which oil is obtainable through wells, which comprises recovering occluded gases separating from oil in a plurality of said wells; testing to determine the relative amount in such removed gases, of methane in comparison with the total amount of gases from methane through at least the pentanes, separately for each of said plurality of wells; and correlating such relative amounts for said wells with the geographical location of the respective wells to obtain an indication of those areas in which said wells have the highest and lowest gas columns.

15. A method of obtaining an indication of the highest and lowest gas columns in an oil reservoir from which oil is obtainable through wells, which comprises recovering occluded gases separating from oil in a plurality of said wells; testing to determine the relative amount in such removed gases, of methane in comparison with butane, separately for each of said plurality of wells; and corre-

lating such relative amounts for said wells with the geographical location of the respective wells to obtain an indication of those areas in which said wells have the highest and lowest gas columns.

16. A method of obtaining an indication of the gas to oil contact points in an oil reservoir from which oil is obtainable through wells, which comprises recovering occluded gases separating from oil in a plurality of said wells; testing to determine the relative amount in such removed gases, of propane in comparison with butane, separately for each of said plurality of wells; and correlating such relative amounts with the geographical location of the respective wells to obtain an indication of the gas to oil contact points in the areas represented by said wells.

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